UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA
Faculty of Natural and Agricultural Sciences

UNDERSTANDING CLIMATIC-LANDSCAPE-HYDROLOGICAL INTERACTIONS AT A MESO-SCALE TO GUIDE GLOBAL CHANGE ADAPTATION: A STUDY IN THE KALEYA RIVER CATCHMENT, ZAMBIA

by

Moses Ngongo Chisola

Submitted in partial fulfilment of the requirements for the degree

PhD Water Resource Management

in the Faculty of Natural and Agricultural Sciences,

University of Pretoria

Pretoria

29 April 2022

Supervisor

Prof. Michael van der Laan

Abstract

This study examined the climatic-landscape-hydrological interactions in a catchment facing landscape fragmentation, agricultural intensification, and increased climatic risks. The study took a holistic approach by examining past, present, and future interactions using the lenses of the green-blue water approach to devise interventions for improved water storage and management in the case study of the Kaleya River Catchment (about 750 km^2) of southern Zambia. The results could be extrapolated to other semi-arid areas with similar hydro-geological and climatic settings.

To assess the past interactions, a simple landscape hydrology approach was developed and applied to determine factors explaining seasonal water availability and provide insights on how landscape components could be enhanced to augment natural river flows and reduce sediment loss. Based on the Variable Importance in Projection (VIPs), results showed that seasonal climatic and weather extremes involving rainfall intensities, rainfall variability and dry spell length were more important than annual rainfall totals in explaining seasonal water availability. Additionally, patchiness of cover was more important in explaining seasonal water availability than the percentage of cover type in the landscape (PLAND). The Patch Density (PD) and Largest Patch Index (LPI) of reservoirs were the main landscape pattern stressors, alongside percentage of cover type metrics involving PLAND of irrigated cropland and reservoirs. But the LPI of forestland positively explained seasonal river flows. The study recommended that water resource interventions in the region must adapt more to changing seasonal rainfall characteristics than to annual rainfall totals. Additionally, regeneration of larger forest patches could improve river flows.

To understand the climatic-landscape-hydrological interactions in the present, naturally occurring stable water isotopes [deuterium ($\delta\ ^{2}H$) and oxygen-18 ($\delta\ ^{18}O$)], hydro-chemical

parameters [chloride (Cl^{-1}) and electrical conductivity (EC)] were used as tracers. Based on the combination of end member mixing analysis and mixing model analysis, the major streamflow sources could be evaluated.

The results revealed that stormwater runoff from non-irrigated areas (43 ± 13) %, the perennial spring (39 ± 21) % and stormwater runoff from irrigated areas (18 ± 17) % were the major streamflow sources in the rainy season. Streamflow sources in the dry season were different upstream and downstream, thereby reflecting different water use dynamics in the catchment. In the upstream catchment, the perennial spring at the river source (65 ± 15) % and irrigation return flows (35 ± 15) % were the dominant streamflow sources. In the downstream part of the catchment, dry season streamflow was mainly attributed to irrigation return flows (73 ± 15) % and wastewater (27 ± 15) %, both associated with water originally transferred in from the adjacent Kafue River through an intra-basin water transfer scheme. It was found that this water plays an important role in sustaining streamflow in the lower part of the catchment before discharging back into the Kafue River. It was thus recommended that efforts to improve irrigation efficiency in the lower catchment must simultaneously ensure downstream flows are maintained.

Based on the findings of the past and present interactions, it was noted that irrigated agriculture had two contrasting effects on dry season flows depending on the source of irrigation water. In the upper and middle catchment where irrigation water was sourced from the Kaleya River, irrigation reduced dry season flows despite some contributions from return flows. In the downstream part of the catchment where irrigation water comes from the neighbouring Kafue River (intra-basin transfer), irrigation increased dry season flows through return flow contributions to the lower Kaleya River.

Having better understood the climatic-landscape-hydrological interactions of the past and present, the potential future changes in climate and their effects on blue water flow (streamflow), green water flow (evapotranspiration – ET) and sediment load were evaluated. This was aimed at getting a holistic overview of the interactions so that management interventions could anticipate the future changes as this is necessary for long-lasting beneficial effects. Two Global Climate Models (GCMs) [MICROC5 and MPI-ESM-LR] and an ensemble (mean) dataset from five GCMs that had the highest Nash Sutcliffe Efficiency (≥ 0.29) and Heidke skill score (≥ 85%) for the Kaleya River Catchment were used to account for uncertainties in GCMs. The Soil and Water Assessment Tool (SWAT) hydrological model was calibrated and applied stochastically (to account for parameter uncertainty) and used to evaluate impacts of climate change on streamflow, ET, and sediment load. The period 1970 – 2005 was used as the baseline, while 2021 – 2050 was the future.

Results based on the ensemble (mean) predicted a 6% and 12% increase in annual rainfall and a 1˚C and 2˚C increase in temperature compared to the baseline under the RCP 4.5 and RCP 8.5 scenarios, respectively. These changes were also accompanied by predicted increase in rainfall intensities. It was further predicted that maximum one-day rainfall would increase by 3% and 20% under the RCP 4.5 and RCP 8.5 scenarios, respectively. Additionally, the GCMs generally predicted increased number of Consecutive Dry Days (dry spell length) by about 2%–10% over the baseline.

Taking the median (M95PPU – defined as the 50% uncertainty level for the hydrological model), and the GCMs ensemble mean climate, a 31% (9,675 m^3 day $^{-1}$) increase in annual streamflow was predicted under the RCP 8.5, accompanied by a sediment load increase of 144% (2,175 tonnes year^{-1}) over the baseline. For the RCP 4.5 scenario, streamflow was predicted to increase by 21% (4,523 m^3 day^{-1}), accompanied by sediment load increase of 65% (994 tonnes $year^{-1}$). With respect to green water flows, there was a predicted 2% (9mm) increase in annual ET under the RCP 4.5 scenario, and no change under the RCP 8.5 scenario. While climate change was predicted to increase water availability in both the rainy and dry seasons, landcover change could reverse the potential blue water gains in the dry season and reduce green water storage by about 13%.

Further, the study evaluated the efficiency of Nature-based Solutions (NbSs) for managing increased rainfall intensities and the predicted increase in rainy season surface runoff and sediment load under different climate change scenarios. The NbSs virtual experiments were conducted using SWAT in SWAT-CUP. The reforestation NbS predicted the largest reductions in surface blue water (surface runoff) by 74% under the historical climate, 69% under the RCP 4.5 and 62% under the RCP 8.5 climate scenarios. Reforestation further resulted in predicted increase in deep aquifer recharge by 39% (historical), 26% (RCP 8.5 scenario) and 23% (RCP 4.5). Additionally, it was predicted that baseflow contribution to streamflow would increase by 11% (historical) and 2% (RCP 8.5) but not under the RCP 4.5 scenario (-2%). Green water flows (evapotranspiration) were predicted to increase by 3% (both RCP 4.5 and RCP 8.5%) and 2% (historical).

Under the recharge structures NbS, it was predicted that surface runoff would reduce by about 2 - 4%, baseflow contribution to streamflow and deep aquifer recharge would increase by about 4%, without any change in ET under all climate scenarios. Conservation tillage NbS had a negligible predicted effect on water balance components at a catchment scale, suggesting that the water benefits could mainly be at a field scale. However, the effects of Conservation tillage on sediment load were noticeable even at a catchment scale.

On sediment load, the highest change was predicted under the recharge structures NbS (-34% historical, -24% RCP 4.5 and -15% RCP 8.5 scenario), followed by reforestation (-15% historical, -7% RCP 4.5 scenario and -6% RCP 8.5 scenario) and conservation tillage (-4% historical, -2% RCP 4.5 and -1% RCP 8.5 scenario). From the green-blue water perspective, it was concluded that these nature-based solutions could assist in managing the increased rainfall and its intensities, and the ensuing high rainy season surface runoff and sediment load. The NbSs could thus assist in storing rainwater in the catchment for longer periods by converting it to deep groundwater, and baseflow and increasing the productive green water flows. The NbS could also be effective in sediment load management.

In conclusion, the interactions of the changing landscape patterns with the changing climate and weather extremes and the effects on local green and blue water availability were investigated in this study. Overall, the study found that landscape pattern changes (patchiness of cover in addition to percentage of cover) amplify the negative effects of the changing climatic and weather extremes in the past, present, and future periods. But if well designed in form of NbS interventions, the landscape patterns could be used to manage the effects of climate change whereby the increasing rainfall intensities could be taken as a resource (not a case) for improving local water storage, and productivity. This could assist in building resilience to other climatic extremes such as dry spells, rainfall variability and increasing air temperatures.

Keywords: green-blue water, nature-based solutions, resilience, sediment load, stable water isotopes, SWAT

Abbreviations and Acronyms

BMP – Best Management Practice

CDD – Consecutive Dry Days

CMIP – Coupled Model Inter-comparison Project Phase

CORDEX – Coordinated Regional Climate Downscaling Experiment

CWD – Consecutive Wet Days

EMMA – Endmember Mixing Analysis

GCM – Global Climate Models

IBWT – Intra-Basin Water Transfer

KASCOL – Kaleya Smallholder Company Limited

NbS – Nature-based Solution

PCA – Principal Component Analysis

PLSR – Partial Least Squares Regression

PRCPTOT – Total rainfall

R10MM – Average number of days with heavy rains in a year

RCP – Representative Concentration Pathways

RX1DAY – One-day rainfall intensity

SASSCAL – Southern African Science Service Centre for Climate Change and Adaptive Land Management

SRES – Special Report on Emissions Scenarios

SWAT – Soil and Water Assessment Tool

TMM – Mean daily air temperature

TXX – Maximum value of daily maximum air temperature

UNZA – University of Zambia

UP – University of Pretoria

WARMA – Water Resources Management Authority

WEAP – Water Evaluation and Planning

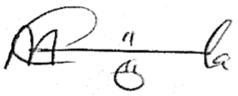
ZMD – Zambia Meteorological Department

$\delta\ ^{18}O$ – oxygen-18

$\delta\ ^{2}H$ – deuterium

Declaration

I, Moses Ngongo Chisola, hereby declare that this thesis, submitted for the degree PhD Water Resource Management, at the University of Pretoria, is my own work and has never been submitted at this or any other university. The thesis results from my own research work, except where acknowledged.



M.N Chisola

29th April 2022

Acknowledgements

I thank the German Academic Exchange Service (DAAD) for funding my study through a PhD scholarship. I also thank Dr Aceme Nyika, Mrs. Ncuthukazi Tshabalala and Ms. Onalerona Matlawe who coordinated this scholarship at the University of Pretoria. I extend my appreciation to Ms Mikateko Ngobeni and all the staff at the Graduate Support Department of the University of Pretoria under the leadership of Dr Nyika for facilitating training in statistical data analysis during this PhD.

I thank the Water Resources Management Authority (WARMA) of Zambia for providing historical streamflow and water allocation data and the Zambia Meteorological Department (ZMD) for the weather data. Professor Henry Sichingabula of the University of Zambia is also appreciated for providing some of the field equipment used in this study.

I also thank the Environmental Isotope Laboratory at the iThemba LABS in Johannesburg, South Africa for analysing stable water isotope samples free of charge and the Environmental Engineering Laboratory, University of Zambia, Zambia for analysing the water quality parameters at a discounted charge. I also thank my supervisor, Professor Michael van der Laan, who from time to time, met the costs for software and data analysis. I also extend special thanks to Professor Keith L. Bristow for the suggestions he made during proposal development and drafting of the first journal article for this PhD.

Finally, I would like to thank my wife Mistrida, my two sons John and Luke, and my recently born daughter Ariana, for their support, patience, and encouragement.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background

As the human population in sub-Saharan Africa grows, there is increased demand for water to drive agricultural intensification to meet food needs and economic growth. Accordingly, water is central to economic development and ecosystem health (Falkenmark and Rockström, 2010, Harou et al., 2020). However, the changing climatic regimes are expected to severely affect the water sector by causing either too much or too little water at wrong times (Falkenmark and Rockström, 2010).

Owing to the drought in the 2018-2019 season (SADC, 2019), there was shortage of water for food and hydro-electricity generation resulting in power cuts across the Southern African Development Community (SADC), with negative effects on the economies (SADC, 2019, Prinsloo and Matema, 2021). Following this drought, over 41 million people in the SADC region were declared food insecure (Prinsloo and Matema, 2021). In Zambia, the population affected by food insecurity was estimated at over 2.3 million (SADC, 2019). This is a demonstration of the need for water security in the context of the dynamic climatic regimes, that are becoming more extreme.

In addition to the changing climatic regimes, changes to the landscape in the quest for development also tend to negatively affect water quantity and quality. Most river basins around the world have been drastically altered and are now composed of a mosaic of forest, bush/scrubland, agriculture, barren land, and built-up areas (Chen et al., 2013). Hence, there is growing interest on the question of how changes in landscape patterns related to cover type are affecting hydrological processes (Fu et al., 2005).

Most of the hydrological models so far only consider the percentage of a landcover type in the catchment. Other aspects related to the configuration of the cover type patches are often not explicitly considered despite the rapidly fragmenting landscapes. In this regard, there is growing research interest in integrating landscape metrics (indices of landscape pattern) developed by scholars in the field of landscape ecology to explain the observed hydrological fluxes (Albalawneh et al., 2015, Ekness, 2013, Epting, 2016). This integration could help to better understand the feedback loops between landscape patterns and hydrological processes under a changing environment towards identifying solutions for building resilience of water resources (Ponette-González et al., 2015).

Building more resilient communities and landscapes will require putting water and landscape management to the centre of climate change adaptation initiatives (Harou et al., 2020). However, water resource management policies and other national policies of countries are rarely designed to build resilience and respond to the changing hydro-climatic regimes. Hence, it is not surprising that the subject of creating more resilient water resources was prominent at the 25th Conference of Parties (COP25) in Madrid, Spain, in 2019 (Harou et al., 2020).

Several definitions of resilience exist. In this study, resilience refers to the ability of a socio-ecological system to withstand a disturbance arising from the landscape and/ or climate change or to recover quickly, and transform to still be able to function properly under the changed conditions (Smith and Barchiesi, 2009, Smith et al., 2019). The resilience paradigm (Holling, 1973, Fiering and Holling, 1974, Zalewski et al., 1997, Smith and Barchiesi, 2009, Raymond et al., 2017, Smith et al., 2019) as espoused through the green-blue water approach (Falkenmark et al., 2004, Falkenmark and Rockström, 2010) can provide an analytical framework for better integrating landscape effects in catchment hydrology studies under a changing environment.

The green-blue water approach recognises the need to promote diversity in water resources management by managing for both blue water (water in streams, river, reservoirs, lakes, and deep groundwater) and green water (soil moisture and evapotranspiration) (Falkenmark et al., 2004, Falkenmark and Rockström, 2006, Falkenmark and Rockström, 2010, Falkenmark et al., 2014). The approach also recognises the role that landscape level interventions could play in managing the partitioning of rainfall into blue and green water (Falkenmark and Rockström, 2010, Falkenmark et al., 2014, Rockström et al., 2014).

More recently, the concept of Nature based Solutions (NbSs) has emerged and is been promoted by several actors, among them, the International Union for Conservation of Nature (IUCN) (Cohen-Shacham et al., 2016). Nature based Solutions (NbSs) are seen as interventions based on natural features and processes that can be used to buffer, manage sustainably and restore natural and degraded ecosystems, while simultaneously addressing the societal challenges such as livelihoods adaptively, for the benefit of both people and ecosystems (Cohen-Shacham et al., 2016).

This PhD study takes the position that the concept of Nature-based Solutions could fit into the green-blue water framework as a landscape level intervention mechanism. The expected outcomes would be more resilient water catchments that are able to cope and/or transform so as to still provide water and support dependent livelihoods and ecosystems under changing climatic regimes (Smith et al., 2019). Therefore, this study is concerned with the assessment of the climate, landscape and hydrological interactions, and evaluation of interventions towards improved water resources management under global change.

The term ‘global change’ in this study is taken to mean the changing climate, and landscape patterns, and could include the increasing water demands arising from population growth, especially from a more populous and prosperous middle class. This definition is similar to the one used by the Czech Global Change Institute (https://www.czechglobe.cz/en/global-change/he, accessed on 12/10/2022) which understand global change as changes to the climate, landscape, ocean and ecosystem productivity, that affect the earth’s ability to sustain life. They acknowledge that although it is a two-word term, it includes many interacting components. In this thesis, the interacting components are climate change, landscape change and hydrological processes. The term ‘changing environment’ in this study is a collective one and encompasses the changing climatic and landscape patterns. Environmental change is thus used interchangeably with global change.

1.2 Problem statement

Among the challenges in achieving more resilient water resources under global change, is the inadequate understanding of the interactions between changing climate and landscape patterns, the impacts on hydrology and the risks arising from this inadequacy in understanding (Harou et al., 2020). Added to this, is increased uncertainties in climate change projections, especially at smaller spatial scales (Smith et al., 2019), considering that effective climate action requires us to ‘think globally and act locally’ (Hoff, 2015, Chang, 2021). There is thus need for increased focus on sub-catchments at a meso-scale (Falkenmark and Rockström, 2010). Meso-scale catchments (10 to 10,000 km^2) are ideal for more efficient protection and management of water resources under global change as they represent the scale at which water resources are managed (Uhlenbrook et al., 2004, Hoff, 2009, Falkenmark and Rockström, 2010).

The meso-scale provides an opportunity to manage rainfall partitioning and allow for effective green and blue water management. Green water (soil moisture, ET) can support crop production and ecological resilience at a local scale while blue water (runoff, streamflow, groundwater, reservoirs) can support socio-economic activities within and beyond the local scale (Falkenmark and Rockström, 2010, Du et al., 2019). A gap remains in terms of understanding the climatic-landscape-hydrological interactions under a changing environment at the scale of tributary channels (sub catchment scale) on which millions of people depend for livelihoods. Already in Zambia, water conflicts among upstream and downstream users are emerging in the meso-scale sub-catchments (Mucheleng'anga et al., 2002, Uhlendahl et al., 2011, Scheumann and Phiri, 2018).

Thus, to build more resilient catchments, improved understanding of the key climatic and landscape pattern changes and how they are affecting intra-seasonal water availability is needed. Among the specific gaps to address include:

i. Inadequate understanding of what climatic, landscape (land use composition and configuration) characteristics are important in explaining observed changes in intra-seasonal water availability in the rapidly fragmenting semi-arid landscapes (Malmer et al., 2010, Guzha et al., 2018), to inform adaptive management.
ii. Uncertainties in the assessment and understanding of streamflow source dynamics in water-stressed, semi-arid sub-catchments undergoing agricultural intensification given the large data gaps and poor monitoring gauge networks (Uhlenbrook et al., 2004).
iii. Inadequate studies in sub-Saharan Africa that evaluate streamflow sensitivity to projected climate change especially in meso-scale catchments to anticipate and plan responses to potential impacts on water resources at this scale.

iv. Lack of adequate quantitative data on how future climatic changes could affect the effectiveness of interventions such as Nature-based Solutions (NbSs) in achieving more resilient water resources.

This study aimed to fill these gaps. The findings could better inform water management interventions under a changing environment.

1.3 Aim, research questions and hypotheses

The study aimed to understand the climatic-landscape-hydrological interactions of the past, present, and future for improved management of sub-catchments under global change. To achieve this, the following research questions were asked:

i. What are the trends in seasonal climatic/weather, landcover composition and configuration patterns in the case study catchment (Kaleya River Catchment, Zambia)?

ii. What are the main interactions among landscape components and climatic/weather extremes that are important to inform landscape level water resource management interventions in a heterogenous catchment such as the Kaleya in Zambia?

iii. What sources may have dominant contributions to streamflow in a heterogenous semi-arid sub-catchment undergoing agricultural intensification such as the Kaleya River Catchment?

iv. How are future climatic extremes likely to change at a local scale in Kaleya River Catchment and how may these affect water availability with respect to blue water flow (streamflow), green water flow (evapotranspiration) and sediment load?

v. How might landscape change (cover) interact with the changes in climate to affect water availability and sediment load in the case study catchment?

vi. To what extent would NbSs be effective in managing the future climatic changes to increase green and blue water availability at a local scale in the case study catchment?

Objective 1: To examine the factors explaining intra-seasonal water availability from among the landscape and climatic patterns, using simple and measurable climatic and landscape pattern attributes derived from historical time series of climatic, landcover and hydrological data.

Hypothesis 1: Landscape configuration and seasonal climatic/weather extremes are more important in explaining local scale water availability than landscape composition (percentage of cover in the landscape) and annual climate totals.

Objective 2: To investigate the dominant streamflow sources in the catchment using tracer-based techniques (based on the third research question).

Hypothesis 2: While rainfall-runoff processes remain important streamflow sources, irrigation return flows and wastewater are the dominant contributors of dry season streamflow in the case study catchment.

Objective 3: To assess the future changes in climatic and weather extremes for improved understanding of the individual and combined climate change - landcover effects on water availability (Based on the fourth and fifth research questions).

Hypothesis 3: Climate change will increase blue (streamflow), green water (soil moisture and ET), and sediment load, but landcover change will reverse the positive climate change effects on water availability and amplify the negative ones.

Objective 4: To evaluate the efficiency of various nature-based solutions (NbSs) in increasing water availability and reducing sediment load under various climate change scenarios.

Hypothesis 4: Nature-based solutions will help to manage rainfall and sediment load by increasing both green and blue water storage at a local scale regardless of the changes in climatic and weather extremes.

1.4 Analytical framework

The study took a multi-step approach combining various tools and methods to holistically assess the climatic-landscape-hydrological interactions of the past, present, and future (Figure 1-1), from 1970 - 2050. In the first step, a landscape hydrology approach was developed and used to assess the past interactions. The approach was based on observed discharge data, indices of historical extreme whether/climatic events along with landscape composition and configuration metrics derived through satellite remote sensing image analysis. The Partial Least Squares Regression (PLSR) was then implemented to detect the climatic and landscape patterns affecting seasonal water availability and to identify the potential NbSs required to augment seasonal streamflow.

Informed by the identified landscape pattern stressors detected in the first step, the second step analysed the interactions of the present time to better understand the rainfall-runoff processes taking place in view of the current landscape structure and water use dynamics. For this, a tracer-based technique using stable water isotopes, hydro-chemical parameters and mixing model analysis was used. The findings further improved the understanding of the interactions and had implications for water allocation management decisions. Additionally, the improved understanding of the hydrological system from this step allowed for better conceptualisation and calibration of the Soil Water Assessment Tool (SWAT) hydrological model, that was needed for the final step.

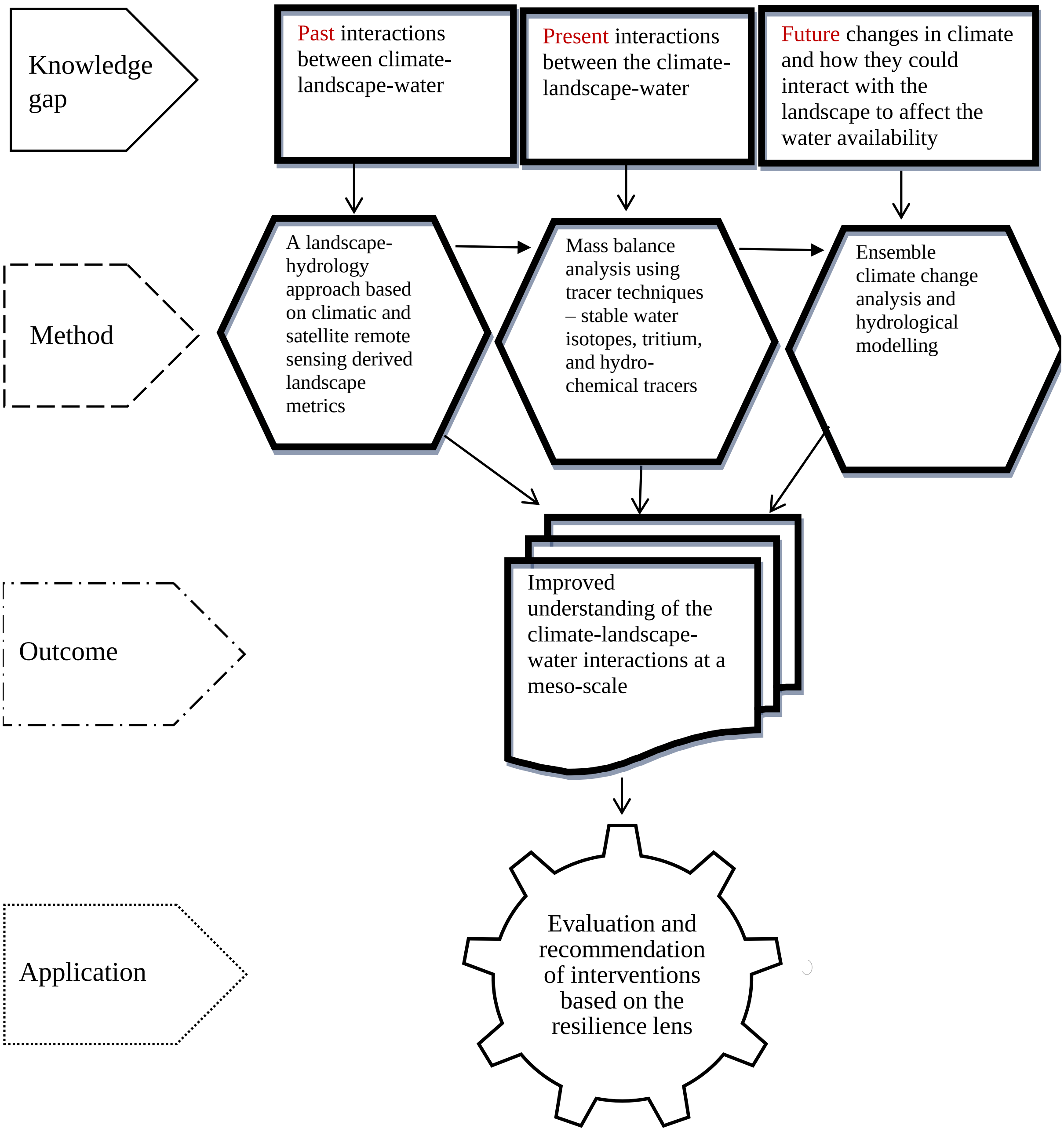


Figure 1-1: A schematic diagram of the analytical framework used in this study

The third and final step used a stochastically calibrated SWAT model along with the ensemble of projected climate data (Global Climate Models) under various climate change scenarios to predict the impacts of future changes in climate and weather extremes on water availability and evaluate the likely effects of the NbS inventions proposed in the earlier steps.

The combination of the novel statistical (PLSR), tracers-based end member mixing analysis, hydrological (SWAT), and ensemble climactic (GCM) models helped to better assess the climatic-landscape-hydrological interactions of the past, present, and future as these methods complemented each other. The landscape (PLSR based) approach had strength in predicting the interactions of the past extreme weather events such as dry spells, onset, and cessation of rains among others and changing landscape patterns in a fragmenting landscape and brought out the main stressors that could have been concealed if the standard hydrological modelling was used.

The mixing model analysis using stable water isotopes had strengthen in predicting the present interactions especially those to do with water use dynamics such as intra-basin water transfer and irrigation return flows. The contribution of these could not have been effectively assessed using the landscape hydrology approach or hydrological modelling. In this regard, mixing model results helped to inform hydrological model calibration. With reduced uncertainties, the hydrological model was useful for predicting flows and for evaluating the impacts of various NbSs interventions proposed from the landscape hydrology and mixing model approaches.

1.5 Description of the case study catchment

The Kaleya is a meso-scale catchment with an area of about 744 km^2. It lies between latitude 15^{o}40’ S to 16^{o}20’ S and longitude 27^{o}30’ E to 28^{o}10’ E (Figure 1-2). From its source at the spring near the Siamakambo Hills in Chikankata District, the Kaleya River drains into the

Kafue River in Mazabuka District. The catchment experiences a sub-tropical climate, with the rainy season typically from Mid-October to early April, and the dry season from Mid-April to early October (Figure 1-3). The average annual rainfall is about 750 mm.

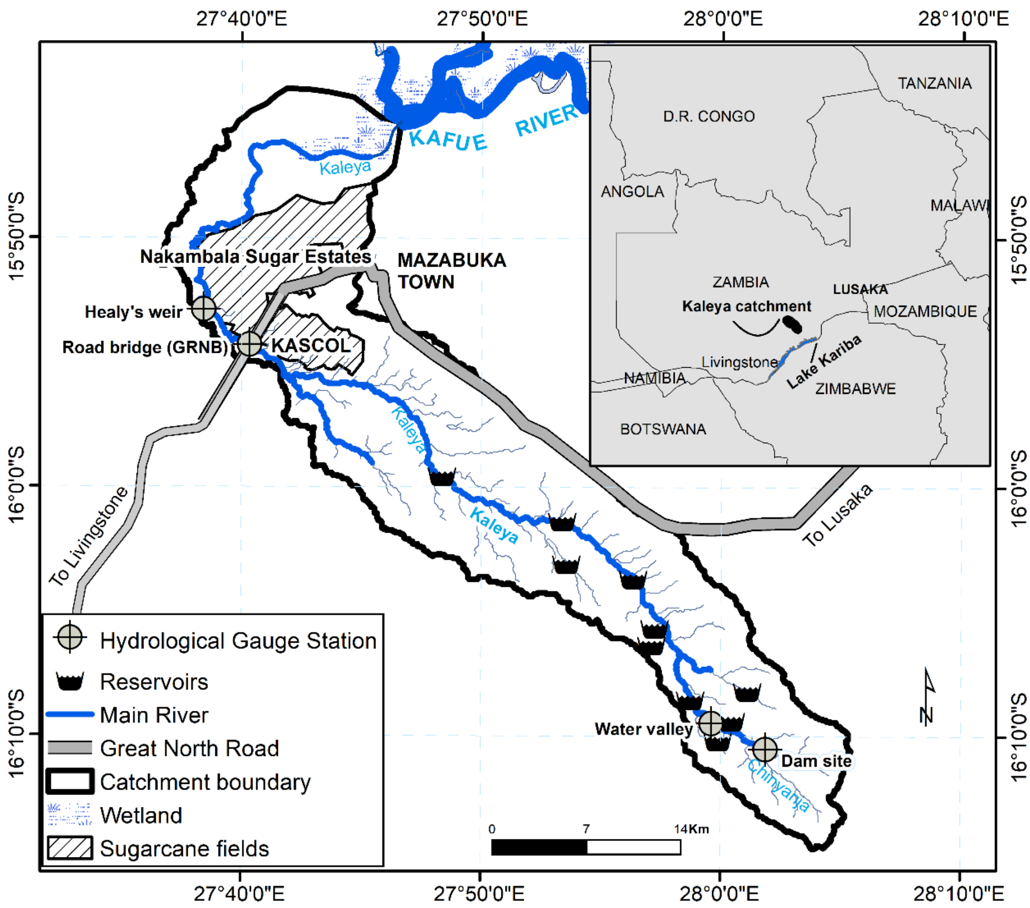


Figure 1-2. Kaleya River Catchment, southern Zambia

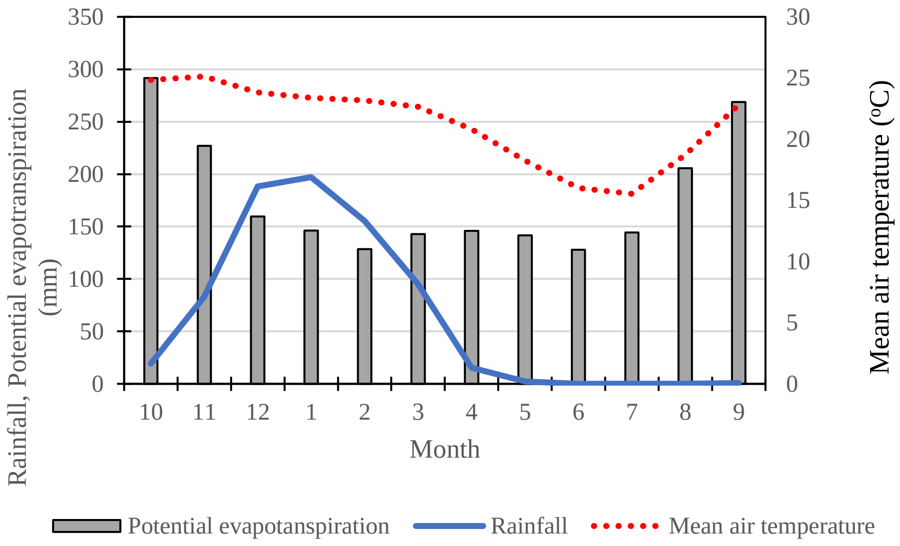


Figure 1-3: Average seasonal climatic patterns in the Kaleya River Catchment

There has been increased agricultural development in the catchment since the 1970s, by mainly three groups: subsistence farmers at the headwaters, commercial farmers in the middle catchment, and the corporate companies running sugarcane estates in the lower catchment. As such, upstream versus downstream conflicts over water use, especially among the subsistence farmers and commercial farmers have been reported (Sichingabula et al., 2015). The subsistence farmers who occupy the upper catchment (63 km^2) are mainly involved in livestock rearing at a small scale, maize (*Zea mays* L.) cultivation in the rainy season, and gardening near the riverbanks in the dry season.

The commercial farmers in the middle catchment take up the largest share of the catchment land area and abstracted water. They most often combine ranching and irrigated agriculture. The main crops grown include wheat (*Triticum aestivum* L.), soybean (*Glycine max* L.), sugarcane (*Saccharum officinarum* L.), lucerne (*Medicago sativa* L.) and other pasture crops.

Due to several dams in this section, most of which are on the main river channel, the formerly perennial river often dries up during the dry season (WWF, 2018b). The sugarcane estates in the lower part of the catchment, which mainly use furrow irrigation, depend on Intra-Basin Water Transfer (IBWT) from the Kafue River.

Arising from the foregoing, the key water resource management aspects revolve around agricultural intensification since the 1970s, increased sediment load especially in the upper catchment (Sichingabula et al., 2000a, Collins et al., 2001, Walling et al., 2001), and siltation in reservoirs in the catchment (Sichingabula et al., 2015). Other aspects include the shift from a perennial middle section of the river to an ephemeral one, and the paradox of sustained river flows in the lower catchment despite the dry middle catchment. Climate and landscape change have for some time been at the centre of discussions as potential drivers of the deteriorating water conditions in the catchment. Therefore, the Kaleya River Catchment provides a good experimental case study for understanding the climatic-landscape-hydrological interactions under a changing environment.

1.6 Overview of the chapters

This section gives the structure of the thesis. The chapters are based on the manuscripts that have arisen from the research work completed from 2018–2021. Two of the manuscripts have been published and two are in draft format.

Chapter 1: Introduction

This chapter gives the background of the study and the problem statement. It also highlights the identified gaps in scientific knowledge, and the ensuing aims and research questions. An overview of the methodological approach and the study area are also given.

Chapter 2: Literature review

A review of the current state of research and water resources management under a changing environment is given in this chapter. The chapter also discusses the approaches used by previous scholars to better understand the hydrology of river catchments. This review is a basis upon which the subsequent chapters on the specific objectives are developed.

Chapter 3: A landscape-hydrology approach to inform sustainable water resource management under a changing environment

This chapter focusses on objective one. It presents the findings of the approach that was developed and applied to understand the past interactions among climate and landscape composition and configuration patterns on seasonal rivers flows. The approach which is based on measurable climatic, landscape and streamflow attributes was able to detect the main climatic and landscape pattern stressors on water availability in the fragmented Kaleya River Catchment landscape.

The findings supported the interpretation of the results in all the subsequent chapters of the thesis, and the identification of extreme weather indices important for assessing future impacts in Chapter five. The chapter also allowed for integration of reservoir parameters to improve hydrological model calibration in Chapter 5, and identification of some of the NbS interventions which served as input in Chapter six.

This chapter has been published as a journal research article *(Chisola et al., 2020)* in the *Journal of Hydrology: Regional Studies.* Author contribution for this paper was as follows: Moses Ngongo Chisola: Conceptualization, methodology, software, writing - original draft.

Prof. Michael van der Laan: Supervision, review, and editing. Prof. Keith L. Bristow: Supervision, review, and editing.

Chapter 4: Quantifying streamflow sources to improve water allocation management in a catchment undergoing agricultural intensification

This chapter focuses on the second objective. The chapter reports on the results of tracer-based techniques applied to evaluate current streamflow sources in the Kaleya River Catchment. The findings have significant implications on water allocation and management. The chapter builds up on the results of Chapter three and provides further understanding of hydrological processes in the case study catchment. Some of the insights gained were useful for the SWAT hydrological model calibration in Chapter five.

This chapter has been published as a journal research article *(Chisola et al., 2022)* in the journal of *Physics and Chemistry of the Earth.* Authorship contribution for this paper was as follows: Moses Ngongo Chisola: Conceptualization, methodology, software, writing - original draft for all the papers. Prof. Michael van der Laan: Supervision, review, and editing. Mike.J. Butler: Laboratory analysis of water samples for stable water isotopes including tritium and editing.

Chapter 5: Future changes in climate and extreme weather events. Implications on streamflow and sediment load

This chapter looks at objective three. It reports on the projected climate and weather extremes and the effects on streamflow and sediment load that water resource management interventions should anticipate in the Kaleya River Catchment. The chapter has been written as manuscript to be submitted to the *Theoretical and Applied Climatology*. The chapters build up from the previous chapters and provides an outlook of the climatic-landscape-hydrological interactions. It also serves as a basis for chapter 6.

Chapter 6: Effectiveness of Nature-based Solutions for water resource and sediment load management under land use and climate change. A green and blue water perspective

The chapter is based on objective four. Informed by Chapter five, this chapter evaluates the efficiency of various nature-based solutions for water resource and sediment load management under various climate change scenarios. The chapter has also been written as manuscript to be submitted to the *International Journal of Disaster Risk Reduction.*

Chapter 7: Conclusions, recommendations, and contributions

A synthesis of all the major findings is provided in this chapter. Conclusions are drawn on the climatic-landscape-hydrological interactions of the past, present, and future. The major interactions in the Kaleya River Catchment and key interventions towards improved catchment management under a changing environment are recommended.

The structure of the thesis is summarised in Figure 1-4. The next chapter will review the climatic-landscape-hydrological interactions. It will form the basis for the other chapters.

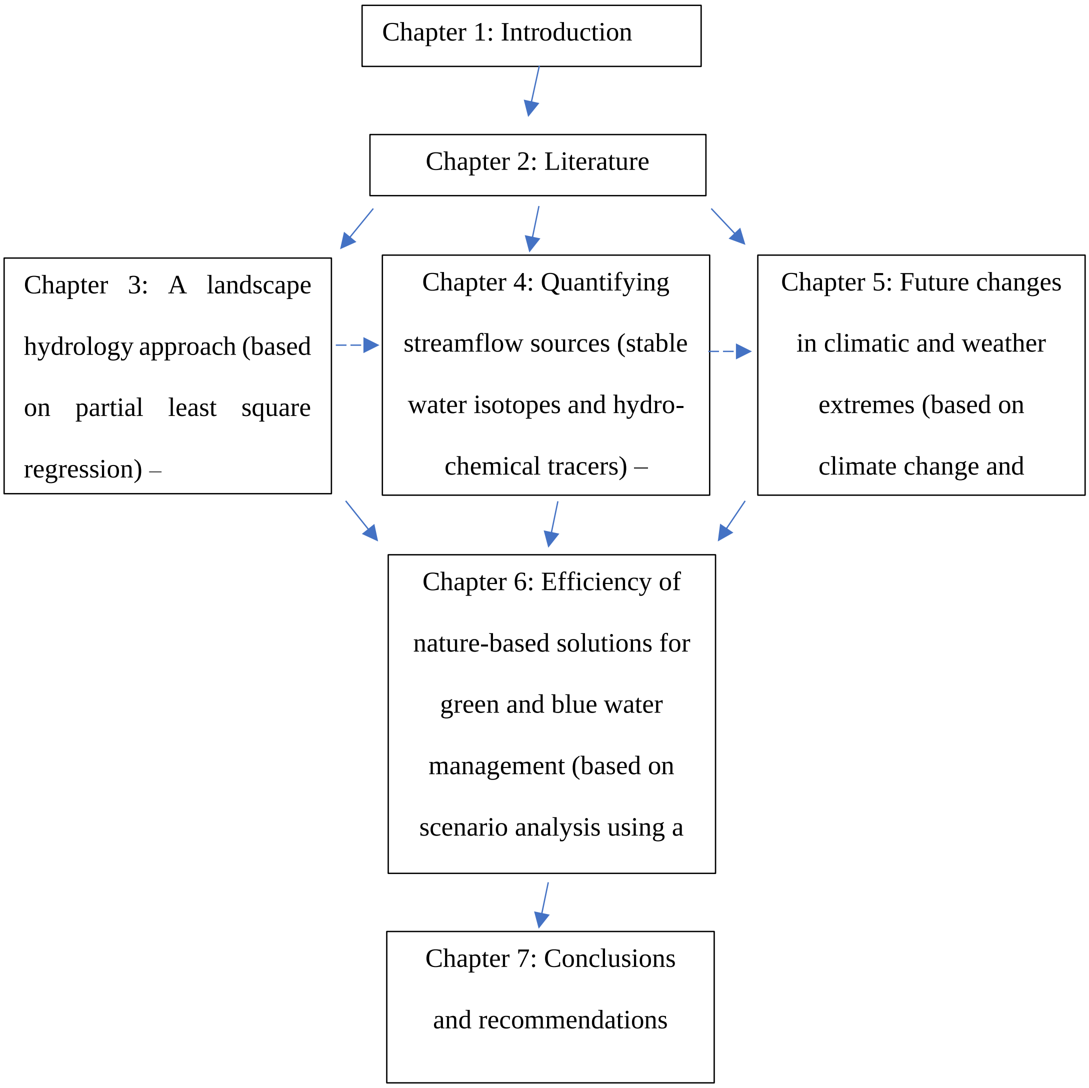


Figure 1-4: Structure of the thesis

Chapter 2

Literature review

This chapter gives a review of important previous studies on climatic-landscape-hydrological interactions and water resources management under a changing environment. It begins with a review of studies investigating global change across the world and in southern Africa, coming down to Zambia. The chapter also looks at the climatic-landscape-hydrological interactions and the assessment methodologies, while highlighting the research gaps in each area which the thesis sought to address. Finally, the chapter conceptualises the climatic-landscape-hydrological interactions upon which the study was based.

2.1 Studies investigating global change across the world

There is increasing research interest in modelling the impacts of climate change on the hydrological regime of catchments. Examples include Hattermann et al. (2014) in Germany, Rouhani and Jafarzadeh (2018) in Iran, Kumar et al. (2017) in the Upper Kharun Basin in India and Leta et al. (2016) in the Heeia Catchment in the United States of America (USA). Climate change impacts were predicted to differ from place to place. While Kumar et al. (2017) in India predicted an increase in both streamflow and evapotranspiration (ET) due to increase in precipitation and air temperature, in Iran, Rouhani and Jafarzadeh (2018) predicted decreases in average quick and low flows in the Gorganrood River Basin due to climate change. Hattermann et al. (2014) in Germany found that the predicted impacts of climate change were not very conclusive in some river basins due to high uncertainties in the models.

Some scholars have gone beyond a sole focus on climate change and have predicted the separate and combined effects of climate with land use change and/ or population growth on hydrology. For example, Mileham et al. (2009) predicted increased future runoff and groundwater recharge due to climate change, and that the future increase in municipal and irrigation water demand could have larger negative impacts on water resources in the basin than the direct positive impacts of climate change. Farjad et al. (2017) used a socio-hydrological framework to understand the co-evolution of climate and land use change in the Elbow River Catchment, Canada, and predicted the separate and combined impacts of these factors on hydrological processes. They noted that there was an interactive effect between climate and land use change whereby they amplified and at times offset each other's effect on runoff processes.

The application of the Representative Concentration Pathways (RCPs) of the Intergovernmental Panel on Climate Change (IPCC) (Moss et al., 2010) in assessing future climatic changes and their implications on water availability has gained popularity. The RCP 4.5 and RCP 8.5 are the commonly used. The RCP 4.5 assumes an intermediate scenario with a radiative forcing of 4.5 W m^{-2} and CO_2-equivalent concentration of around 650 ppm (Faggian, 2021). The RCP 8.5 assumes a 'business as usual' scenario and has a high radiative forcing of 8.5 W m^{-2} resulting from CO_2-equivalent concentration of around 1370 ppm (Moss et al., 2010, Faggian, 2021).

In southeast Asia, Trang et al. (2017) used RCPs 4.5 and 8.5 to understand the impacts of climate and land use change on the Sekong, Sesan, and Srepok River Basin. They predicted that discharge would increase in the rainy season and decrease in the dry season due to climate and land use changes. In the USA, Lee et al. (2018) assessed the effects of climate variability and change on water yield and nutrient load in two small neighbouring catchments using CMIP

5 data under RCP 8.5. They predicted that nutrient yield was higher in the catchment dominated by agriculture.

In summary, the cited studies demonstrate the growing research interest globally to better understand the interactions between changes in climate, land use and hydrological processes.

2.2 Studies investigating global change within southern Africa

Water resources in southern Africa are highly vulnerable to perturbations in the environment due to the high temporal and spatial variability of the hydro-climate regimes. This section gives a climate change outlook and the interactions between climate, land use and population growth as reported in previous scholarly work.

2.2.1 Climate change

Current scientific knowledge mainly stems from previous studies based on trend analysis of observed air temperature and rainfall records and predictions using Global Climate Models (GCMs). The trend analysis results have reported increasing air temperatures in much of southern Africa, even though the magnitudes are highly variable (Kusangaya et al., 2014). Despite historical rainfall records suggesting a decreasing trend in rainfall amounts, the observations are inconclusive as they are mostly not statistically significant, partly due to high variability of rainfall in the southern African region even without climate change (Kusangaya et al., 2014). However, in some regions such as the southern parts of Zimbabwe, significant increasing trends in the number of dry spells have been reported (Sibanda et al., 2018).

Regarding the future climate, studies project air temperature increases of 2 – 5 $^{\circ}$C by 2100, with higher magnitudes mostly reported in drier regions, suggesting they will become even drier and warmer. Some areas of southern Africa are projected to experience increases in rainfall activity (Graham et al., 2011), while others are projected to experience decreases in rainfall ranging from 5 to 23% or more, and increase in flood events separated by longer dry spells (Kusangaya et al., 2014, Conway et al., 2015, Banze et al., 2018). The duration of the rainy season is projected to shorten because the Intertropical Convergence Zone (ITCZ) is likely to shift northwards (Shongwe et al. 2009, Gannon et al. 2014, Lazenby et al. 2018).

In Zambia, trend analysis of historical climate data has shown statistically non-significant declining trends in rainfall (Mubanga and Umar, 2014, GRZ, 2020). On the other hand, statistically significant increasing trends in observed air temperature have been reported in most parts of the country, especially for maximum and mean air temperature (Mubanga and Umar, 2014, GRZ, 2020).

With respect to the future climate projections, the predictions are different in different parts of the country. Based on rainfall distribution, Zambia is divided into three Agro-Ecological Regions (AERs). AER I covers the southern part of the country where the case study catchment is located and receives the least annual rainfall (below 800 mm). AER II covers the middle of the country and receives medium annual rainfall (800-1000 mm), while the AER III covers the northern parts of the country which receive high annual rainfall amounts (> 1000 mm). Based on the foregoing, AER I is predicted to experience increased rainfall under both RCP4.5 and RCP8.5 by 2050 (Mubanga and Umar, 2014, GRZ, 2020, Chisanga et al., 2022). AER II is predicted to experience slight decrease in rainfall under both RCP4.5 and RCP8.5, while AER III is predicted to experience a major decrease in rainfall under both RCPs (Mubanga and Umar, 2014, GRZ, 2020, Chisanga et al., 2022). On the other hand, air temperatures are predicted to increase, with large increases predicted for the AER I (Mubanga and Umar, 2014, GRZ, 2020, Chisanga et al., 2022). However, not all the GCMs predict these changes as some predict in the opposite direction (GRZ, 2020).

2.2.2 Climatic-landscape-hydrological interactions

Several studies in southern Africa have used the predicted climate to assess its implications on water availability using hydrological models. A few examples of such studies are given here. In South Africa, Zhu and Ringler (2012) studied the impacts of climate change and increasing irrigation water demand in the Limpopo River Basin, and predicted that hydrological response was mostly sensitive to changing precipitation patterns. In Zambia, Beck and Bernauer (2011) used a lumped rainfall – runoff model to understand the impacts of climate change and increasing water demand on water availability in the Zambezi River Basin. Strong impacts of non-climatic factors (land use change and increasing water demand) on water availability were predicted. Yamba et al. (2011) predicted reduced inflow into hydro-electricity reservoirs due to projected droughts and increased water demand. Kling et al. (2014) found that projected large-scale irrigation expansion in the Zambezi River Basin could reduce discharge.

Meinhardt et al. (2018) assessed the impacts of climate change and land management on selected catchments in southern Africa, which also included the Luanginga Catchment (about 33,000 km^2), a sub-catchment of the Zambezi. The study used high resolution (25 km) global climate data downscaled by Regional Model [REMO] (Jacob et al., 1995) from the Europe-wide Consortium Earth System Model (EC-Earth) and the European Centre Hamburg Model (ECHAM) Global Climate Models (GCMs). It was predicted that the sub-catchment is sensitive to changes in climate and land management, and that rainfall, runoff, percolation, and flooded area are projected to decrease under both RCP 4.5 and 8.5 scenarios.

Generally, these studies, especially in Zambia, focused on larger river basins with a bias towards impacts on river flows for hydro-electricity generation. More detailed investigations in meso-scale sub-catchments are required to understand the impacts on seasonal water availability. This would extend the current state of knowledge on the impacts of the changing climate and landscape patterns beyond the implications for hydro-electricity generation. Hence section 2.2.4 discusses why more detailed studies are required at a meso-scale.

2.2.3 Accounting for uncertainties in predictions

Different GCMs lead to different predicted future climates that can be used to examine the range of future hydrological changes. Uncertainties remain with respect to what future development pathways will look like, how much Green House Gases (GHGs) will be emitted as a result, and how the climate would react to the different concentrations of GHGs in different places and at different scales, and further still, how society would react to these changes. It is also uncertain in terms of how the hydrological and/or the socioecological-hydrological system would react.

There is thus need to account for structural uncertainty using approaches such as an using ensemble of multiple GCMs (Her et al., 2019). Hydrological models also have their own structural uncertainty which could be accounted for by following the Framework for Understanding Structural Errors (FUSE) (Clark et al., 2008). The FUSE is based on the equifinality concept which states that different combinations of models can lead to the identical model performance and on the premise that a generic model is better than one model (Clark et al., 2008).

In addition to structural uncertainties, there are also parameter uncertainties. Therefore, the hydrological models used to assess climate change effects must consider parameter uncertainty. This could be through stochastic calibration that is based on the identification of possible parameter ranges rather than the often-used deterministic approach, which is based on single parameter values for calibration parameters (Abbaspour et al., 2018, Abbaspour, 2022). In this study, the structural uncertainty of the GCMs was considered using multiple of GCMs and their ensemble, while one hydrological model structure built in SWAT was used but incorporating stochastic calibration of the model parameters.

2.2.4 A case for an increased research focus on sub-catchments

Given the dominance of large river basin studies in published research, the need for improved research focus on sub-catchments has been raised (Falkenmark and Rockström, 2010, Kusangaya et al., 2014, Leta et al., 2016, Olsson et al., 2016). Some first-order streams could become almost permanently dry due to low precipitation and increased evapotranspiration (ET) (Schindler, 1997, Schindler, 2001, Brooks, 2009, Zhu and Ringler, 2012). In other areas, it is postulated that human activities such as agriculture, settlement, deforestation, and industrial development in general could have greater negative impacts on water availability in micro- to meso-scale catchments than climate change (Olsson et al. 2016). Whatever the case, millions of riparian livelihoods dependent on small rivers and reservoirs could become negatively affected by impaired hydrological functioning of sub-catchments, thus the need for adequate information on the climatic-landscape-hydrological interactions to guide adaptation process.

Semi-arid areas such as much of southern Africa have high heterogeneity in terms of vegetation patterns, topography, and microclimate, thus making generalisations at larger spatial scales less useful (Newman et al., 2006, Chen et al., 2013). As water resources are managed at the meso-scale, there is need to improve scientific focus and understanding of the impacts of climate and landscape pattern changes on hydrological response and water availability in sub-catchments (Kusangaya et al., 2014). Shifting assessments and water resource management interventions from predominantly river basin scale to meso-scale sub-catchments could create more resilient sub-catchments (Falkenmark and Rockström, 2010). Resilient sub-catchments could then be the building blocks for sustainable water resources at a larger river basin scale.

2.2.5 The green-blue water approach to water resource management

The green-blue water approach is a landscape-based approach which recognises that precipitation is partitioned by the landscape into ‘green’ and ‘blue’ water (Falkenmark et al., 2004, Falkenmark and Rockström, 2006, Hoff, 2009). Green water is the water that enters the soil and is later ‘lost’ as vapour through evaporation and transpiration (Rockström and Falkenmark, 2000, Falkenmark and Rockström, 2006). Green water also includes canopy interception losses (Rockström and Falkenmark, 2000). Blue water is the water in rivers, reservoirs, and aquifers.

Most commonly, water resources management tends to be based on managing blue water, neglecting green water that is equally critical for both human livelihoods and ecosystems survival (Rockström and Falkenmark, 2000, Falkenmark and Rockström, 2006, Hoff, 2009). Even under the blue water bias itself, the focus tends to be on management of water in rivers (discharge/streamflow), yet groundwater is also important as a source of water supply in most meso-scale semi-arid areas. Grey water (household wastewater) is also becoming increasingly important especially in urban and peri urban areas and efforts for its improved management will be needed. However, the focus of this study was primarily on managing rainfall under a changing environment in terms of how it gets partitioned into green and blue water, hence the green-blue water perspective is taken.

The green-blue water approach in semi-arid meso-scale sub-catchments provides a paradigm shift to the management of water resources in several ways. Firstly, the approach recognises precipitation as the basic water resource that needs to be managed (Falkenmark and Rockström, 2006). This means managing the way that precipitation is partitioned into green and blue water, and the trade-offs that may arise. For example, increasing green water flow (ET) could decrease blue water flow (streamflow).

Secondly, the paradigm also highlights green water as another resource at the centre of water management in addition to precipitation and blue water (Hoff, 2009). Green water is involved in biomass production, thus supplying food and other products and services (Falkenmark and Rockström, 2006, Hoff, 2009). Green water is thus important for promoting local resilience at a meso-scale, while blue water could promote resilience beyond the catchment scale. Hence, the green-blue water approach enables downscaling of water resource management from the management at large river basin scale to that of the sub-catchments, the scale at which soil moisture becomes important in supporting terrestrial ecosystems and local livelihoods resilience (Hoff, 2009).

Blue water availability in meso-catchments is threatened by deforestation. Although deforestation could be associated with less groundwater loss due to reduced Evapotranspiration (ET), poor post deforestation land management practices often result in reduced recharge to aquifers due to reduced infiltration (Peña-Arancibia et al., 2019). Reduced recharge may further reduce blue water availability over the long term through reduced baseflow to streams (Peña-Arancibia et al., 2019).

Additionally, although reduced infiltration under deforestation is associated with higher surface runoff generation, this is often accompanied by high sediment loads due to lack of vegetation cover to moderate the erosive action of rainfall and runoff (Sichingabula et al., 2000a, Chisola and Kuraz, 2016) The increased sediment load in turn reduces the storage capacities of rivers and reservoirs (Walling et al., 2001, Chomba, 2017, Muchanga et al., 2019). As a result, rivers and reservoirs fill up more quickly due to reduced capacities, and much of the storm runoff is lost rapidly out of catchments to the seas and oceans. The remaining water dries up early, thereby threatening blue water availability in the local catchment (Muchanga et al., 2019).

In this regard, the green-blue water approach is relevant for addressing contemporary water management challenges in semi-arid meso-scale areas under the changing climate and landscapes. However, little scholarly attention has been paid to the green-blue water approach as a management concept. The concept advocates for Integrated Land and Water Resources Management (ILWRM) at smaller spatial scales such as the meso-scale (Falkenmark and Rockström, 2006). Hence the green-blue water approach has been identified as relevant in this study for further evaluating the climatic-landscape-hydrological interactions at a meso-scale especially with respect to the future changes in climatic and weather extremes and the required landscape level interventions.

2.2.6 Nature-based Solutions

The concept of Nature-based Solutions (NbSs) has in the recent past become increasing popular in climate change adaptation and catchment management discourse (Keesstra et al., 2018, Collier and Bourke, 2020, Reaney, 2022). Most of the NbS interventions such as reforestation and improved tillage and other land management practices are not new in catchment hydrology as they are among the best management practices (BMPs) often touted. However, it could be argued that NbSs are not just green infrastructure (nature and natural process) interventions. They are specifically designed to address many inter-connected issues to generate ecological, environmental, and socio-economic co-benefits and therefore fall within the realm of Ecosystem based Adaptation (EbA) (Collier and Bourke, 2020, Seddon et al., 2020a). EbA is a concept about increasing resilience of people to climate change using ecosystems and ecosystem services (Seddon et al., 2020b).

Therefore, although the two concepts have developed separately, this PhD study takes the position that the NbS concept sits well with the green-blue water approach. The NbS could provide a mechanism for implementing the landscape level interventions envisioned in the green-blue water approach. Mainly NbS target at restoring or promoting soil health and reducing landscape connectivity (Keesstra et al., 2018). In so doing, NbS can be used to convert high rainfall intensities into less runoff, thereby reducing flood and erosion risk, and increasing local scale water availability by increasing green water (soil moisture) and blue water (groundwater) (Keesstra et al., 2018). This could in turn reduce drought risk and increase resilience of water resources and people.

Collier and Bourke (2020) have argued that grey infrastructure (engineering structures) depreciates with time resulting into high maintenance costs, while green infrastructure (nature and natural processes) using NbSs appreciates with time. However, the effectiveness of NbSs in achieving the expected goals on water availability in the context of future climatic changes remain uncertain (Seddon et al., 2020a). The evaluation of the NbS efficiency under various climate change scenarios was thus a subject of investigation in this study.

2.3 Conceptualising climatic-landscape-hydrological interactions under a changing environment

The nexus approach has traditionally focused on the interactions among climate-water-energy-food, and mainly in large river basins used for hydro-electricity generation as pointed out earlier. This nexus approach could still be conceptualised in meso-scale sub-catchments where hydro-electricity generation is not important. For example, in many meso-scale catchments in Zambia and other parts of southern Africa, vegetation clearance for wood biomass energy (charcoal and firewood) is a major contributor to deforestation (Syampungani et al., 2011, Chirwa et al., 2014, Jha and Schmidt, 2021), which in turn affects the local water resources. Given that agriculture is another major driver of deforestation in these sub-catchments, the impacts on the hydrological regime are potentially similar to those driven by biomass energy exploitation. But large scale mining operations have also been identified among the major drivers of deforestation in Zambia (Shakacite et al., 2016).

These drivers have led to changes in landscape patterns (landscape composition and configuration), which interact with changing climate patterns, resulting in changes in sediment generation, and blue and green water availability. In addition, water management practices such as large-scale irrigation schemes, inter-basin water transfers and water reservoirs also interact with landscape and climatic patterns differently and add pressure on the hydrological regime (Figure 2-1). These interactions need to be well understood and managed because they have wider negative implications on the resilience of water dependent livelihood sources, and terrestrial and aquatic ecosystems.

While catchment hydrology simply deals with climate and landscape interactions and resultant effects on water availability, the assessment of the interactions rarely incorporates landcover configuration aspects such as patchiness of cover which could be becoming important in fragmenting landscapes. This study conceptualises climatic-landscape-hydrological interactions (Figure 2-1) that encompass elements often neglected in most catchment hydrology models and, in the Water-Energy-Food nexus. An improved focus on these interconnections could be important for building resilient water resources in meso-scale sub-catchments under global change. Some of the main interlinkages are summarised in Figure 2-1.

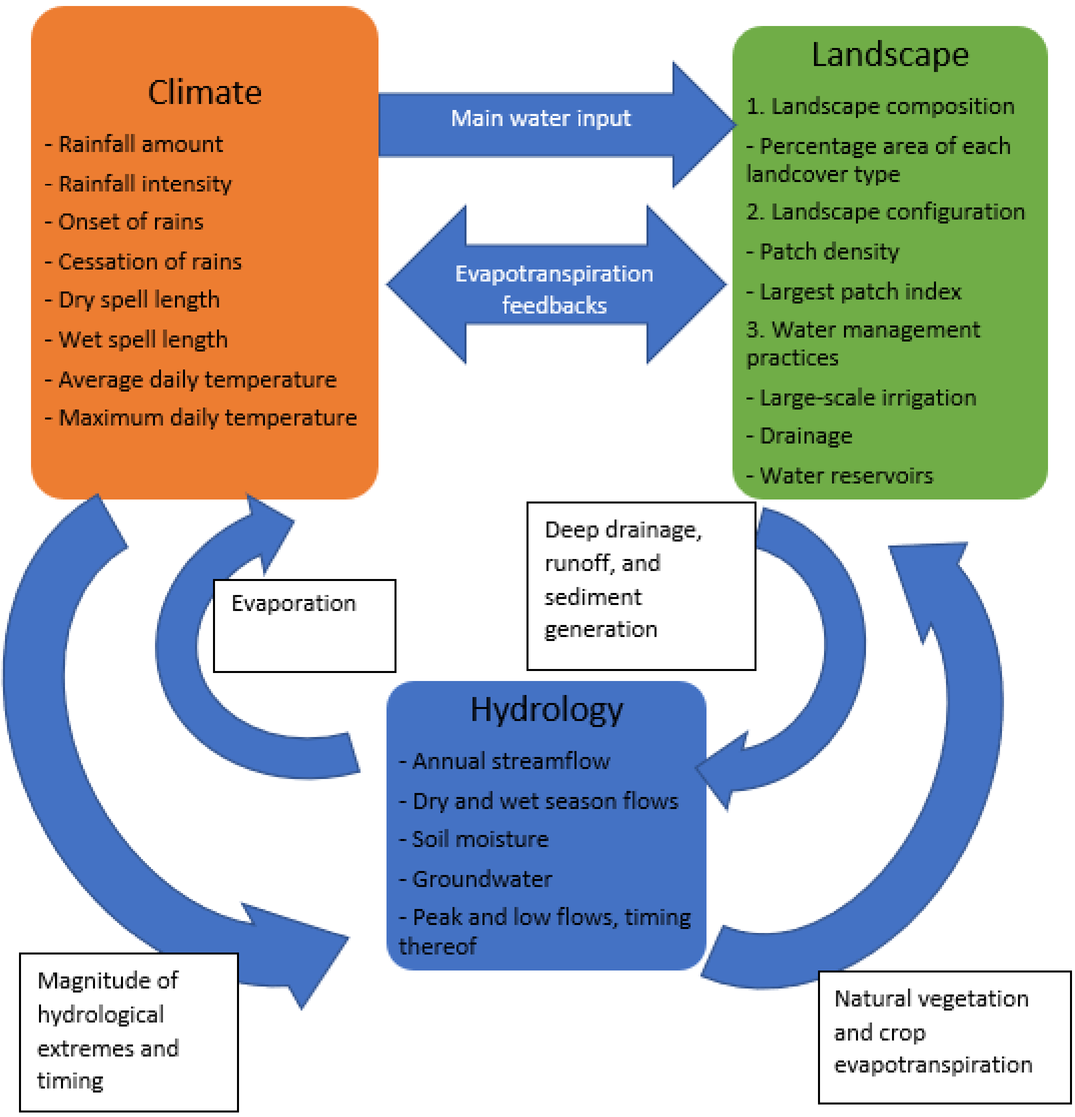


Figure 2-1: Conceptual framework highlighting the main climatic-landscape-hydrological interlinkages

2.4 Assessment and modelling tools for understanding the climatic-landscape-hydrological interactions under a changing environment

To assess and model the complex hydrological processes such as the ones conceptualised in the climatic-landscape-hydrological nexus in Figure 2-1, the eco-hydrological processes paradigm developed from sustainability and resilience thinking could be a starting point (Zalewski et al., 1997). Research in the area of eco-hydrology traditionally focused on understanding the impacts of changing ecological patterns on hydrology and vice versa (Chen et al., 2013). But rather than following the more generic eco-hydrological research, which is mainly based on vegetation-water interactions, there is acknowledgement that most basins have drastically been altered and are thus composed of a mosaic of landcover types and patches (Chen et al., 2013). Hence, there is growing interest on the question of how changes in landscape patterns affect eco-hydrological processes on a landscape scale (Fu et al., 2005). In this regard, assessment tools can range from the use of simple measurable nexus attributes to tracer-based techniques and hydrological modelling. These are reviewed in subsequent sections.

2.4.1 Simple measurable indices and multi-variate statistical analysis

There is increased interest in how and to what extent the landscape ecology concepts can be used to explain hydrological change in a changing environment (Amiri et al., 2019). Several hydrological change studies have attempted to integrate landscape metrics (indices of landscape pattern) from landscape ecology, to explain hydrological fluxes (Ekness, 2013, Albalawneh et al., 2015, Epting, 2016, Gebremicael et al., 2019). This integration helps to understand the feedback loops between landscape patterns and hydrological processes and the functional implications. The field of remote sensing provides a great opportunity in this area.

Remote sensing imagery can be used to generate landcover maps that enable the analysis of the changes in the landscape composition and configuration over time.

Software packages, such as the FRAGSTAT (McGarigal et al., 2012), are useful in extracting landscape metrics from landcover maps. The landscape metrics of interest are those that represent dominance, connectivity, fragmentation, and shape complexity in the landscape. These metrics have been observed to be important for ecosystem functioning (Albalawneh et al., 2015), and their changes can lead to changes in water and nutrient cycles (Hobbs, 1993).

In semi-arid regions, small reservoirs are a common feature. Often their impacts on water availability are not well understood as they tend to be neglected in most studies, partly due to lack of dam management data. However, some research has shown that their ensemble impact could be significant in altering the hydrological regime (Meigh, 1995, Hughes and Mantel, 2010). Small farm reservoirs should therefore be included in the landcover classification and analysis, allowing for the assessment of how reservoir extent and configuration affects local water availability.

Similarly, indices describing climatic and hydrological changes can be derived from historical hydro-climatic time series data corresponding to the historical landcover maps. The interactions are then evaluated using multi-variate statistics. For example, after simulating Gebremicael et al. (2019) used partial least squares regression to assess the individual contribution of landcover types (landcover composition) to hydrological change. Similarly, Woldesenbet et al. (2017) used the Soil and Water Assessment Tool (SWAT) hydrological model and partial least squares regression to evaluate the contribution of each landcover class to changes in hydrological components of runoff, baseflow, water yield and ET although the study fell short at comparing the outputs between the methods since SWAT can also output these per landcover. Amiri et al. (2019) used landscape metrics to explain the lag time of catchments using stepwise multiple linear regression. Chiang et al. (2019) used Pearson's correlation and the SWAT model outputs to identify landscape pattern controls on water and sediment yields.

From these examples, it can be observed that while tremendous progress has been made to better incorporate landcover configuration metrics, the approaches have been biased towards the landscape-hydrology part of the nexus, and yet again neglected the other important aspect, the climate component in the interactions. More recently, Yu et al. (2020) attempted to expand the scope by integrating climatic elements (precipitation, windspeed, sunshine duration and temperature) and landscape pattern metrics to evaluate the impacts on ET in China.

There is need to build on these studies, to fully integrate intra-seasonal climatic and weather extremes, landscape pattern metrics and hydrological parameters for improved understanding of the interactions/stressors in the face of global change. Additionally, the studies so far mostly utilise simulated hydrological data, which can have its own uncertainties compared to observed hydrological data especially in areas that have been extensively dammed such as the case study catchment. Hence, there is need for an approach that can still integrate the climatic-landscape patterns and hydrological variables, without the need for hydrological simulation where long term observed hydrological data is available. Such an approach could mainly be useful in understanding the past evolution of the interactions and was thus presented in this study.

2.4.2 Tracer-based techniques using stable water isotopes and hydro-chemical tracers

To improve the management of river catchments under a changing environment, there is need to also understand the dominant runoff sources resulting from the current interactions. This can allow for better implementation of conservation practices and guide water allocation to various competing needs. However, the hydrometric data required to understand runoff generation processes is often lacking in most river catchments. Tracer techniques could fill the data gaps. The concept behind the tracer-based hydrograph separation models is reviewed.

2.4.2.1 Two-component hydrograph separation model

Solute-based tracers and naturally occurring stable water isotopes have been used to identify the sources of streamflow and thus understand the dominant runoff generation processes and hydrological pathways (Abiye et al., 2015, Camacho et al., 2015, Koeniger et al., 2020, Mokua et al., 2020). The two-component hydrograph separation model helps to identify the time source of runoff (Burns, 2002). The model conceptualises that stream flow could be separated into ‘new’ and ‘old’ water or in other words ‘event’ and ‘pre-event’ water. In this regard, new water is the water from precipitation (rainfall or snow melt), while old water refers to surface storage, soil water and groundwater, which was already present in the catchment prior to the precipitation event (Sklash and Farvolden, 1979). The mass balance equation governing the model has five assumptions (Sklash and Farvolden, 1979, Buttle, 1994):

i. The tracer composition of event water is considerably different from that of pre-event water.
ii. The tracer concentration in event water does not change in space and time or undergoes changes that can be quantified.
iii. The tracer concentration in pre-event water does not change in space and time or undergoes changes that can be accounted for.
iv. The tracer concentration of soil water is like that of groundwater, or the contribution of soil water to streamflow is negligible.

These assumptions suggest that the tracers (isotopic or hydro-chemical) must be conservative at least over short time scales. Hence, the naturally occurring stable water isotopes of deuterium ($\delta\ ^{2}H$) and oxygen-18 ($\delta\ ^{18}O$) are commonly used. Limitations with the two-component model, especially with respect to the fourth assumption led to the development of the three-component hydrograph separation model. This was after the observation that there can be a major contribution of soil water to streamflow and that tracer concentrations in soil water were different from those in groundwater (Kennedy et al., 1986, Dewalle et al., 1988, Klaus and McDonnell, 2013).

2.4.2.2 Three-component hydrograph separation model

The three-component hydrograph separation model allows for detailed investigation of the runoff processes contributing to streamflow. Typically, it attempts to divide the hydrograph into three components: direct runoff, shallow subsurface flow (soil water), and groundwater. In this regard, the term 'component' and 'end member' are often used interchangeably. Two approaches have been used to perform a three-component hydrograph separation.

The first approach is the one tracer three-component model proposed by Dewalle et al. (1988) in which only one tracer is needed to evaluate the contributions of direct runoff, shallow subsurface flow (soil water), and groundwater to streamflow. Often, the tracer would be used to quantify the contribution of subsurface flow and groundwater endmembers, while the direct runoff end member would be estimated from hydrometric measurements and/or calculated from rainfall falling on saturated areas such as the stream channel, and/or impervious surfaces such as built-up and rock outcrops. For example, Dewalle et al. (1988) estimated direct runoff by calculating the amount of runoff generated from channel precipitation (precipitation falling directly on the river/streamflow channel or water body). Uhlenbrook et al. (2002) estimated the direct runoff component based on the percentage of saturated and impervious areas in the catchment.

The alternative, two tracer three-component hydrograph separation model was proposed by Ogunkoya and Jenkins (1993). In this model, most studies combine a stable water isotope tracer (^{2}H or ^{18}O) and a hydro-chemical tracer, often chloride (Cl^{-}) or dissolved silica (Si). Other hydro-chemical tracers often used include acid neutralising capacity (ANC) and electrical conductivity (EC). The two stable water isotopes of ^{2}H and ^{18}O are rarely used together in a full three-component two tracer hydrograph separation model, as they are assumed to carry the same information (Klaus and McDonnell, 2013). Thus, this type of model assumes that (Ogunkoya and Jenkins, 1993):

i. There are three components contributing to streamflow. The first component is direct runoff (channel precipitation and overland flow, both having similar isotopic or hydro-chemical concentrations). The second component of streamflow is the shallow subsurface or soil water flow, and the third component is deep groundwater.
ii. Each of the end members has a unique tracer concentration.
iii. Tracer concentrations of end members may vary temporally during the event (rainfall or snowmelt).
iv. Baseflow could be due to the mixing of shallow subsurface and deep groundwater.

The three-component hydrograph separation model provides information about the geographical source (surface, subsurface, groundwater), while a two-component model provides information about the time source (event or pre-event water) (Burns, 2002).

2.4.2.3 Dominant runoff generation processes in wet and dry catchments inferred from tracer-based techniques

Findings suggesting a negligible contribution of hortonian overland flow (infiltration excess overland flow) to runoff called for the need to extend tracer-based studies to other climatic regions and land uses, outside the humid climate and forested land use that had dominated early work (Burns, 2002, Buttle and McDonnell, 2005). This was to gain further insights into runoff generation mechanisms in other environments. Klaus and McDonnell (2013) observed that most studies conducted in drier climates so far point to the importance of event water (overland flow) in explaining streamflow.

In many meso-scale semi-arid catchments for which this study is a focus, event runoff can make up a significant contribution to streamflow. Pre-event water is usually less due to the limited surface-groundwater connectivity in such areas. For example, in some parts of the Kruger National Park in South Africa, Fundisi (2014) found an overland flow contribution of up to 64% due to the granitic and basaltic geology. But even where the infiltration opportunities are good, saturation excess overland flow has been found to dominate the hydrograph in some areas. For example, McCartney et al. (1998) in Zimbabwe found that once the soil in a dambo had been saturated, event runoff contributed up to 70% to streamflow. Similarly, Riddell et al. (2013) found event water contribution to streamflow of 66% in the Sand River headwater region in South Africa. There are however other studies that have indicated the dominance of pre-event water even within the semi-arid Africa (Wenninger et al., 2008, Hrachowitz et al., 2011, Camacho et al., 2015, Saraiva Okello et al., 2018, Mokua et al., 2020). Hence it appears that the debate on which runoff generation mechanism dominates has not yet been resolved, but the answer would largely depend on the type of the hydrological setting.

There are limited studies in southern Africa focussing on dominant runoff generation processes using tracer-based techniques (isotopic or chemical), especially outside of South Africa and Zimbabwe. Therefore, this study will contribute to filling this gap and add to scholarly literature in a less studied area facing agricultural intensification.

2.4.2.4 Understanding the role of irrigation return flows using stable water isotopes and hydro-chemical tracers

Several studies have used stable water isotopes and/or hydro-chemical tracers to investigate the contribution of irrigation return flow to streamflow or groundwater recharge in catchments of different sizes. The use of stable water isotopes in this regard is based on the assumption that the isotopic composition of irrigation water differs significantly from that found in other end members such as precipitation, soil water, groundwater and streamflow (Vallet-Coulomb et al., 2017).

Among the hydro-chemical tracers, Cl^- has been used widely for determining the contribution of irrigation return flow as it is assumed to be a conservative tracer (Simpson and Herczeg, 1991, Kattan, 2008). The concentration of heavy water isotopes and dissolved ions in irrigation return flows tends to be higher than in irrigation water. This is because lighter isotopes are preferentially evaporated leaving behind heavier ones, and ions such as Cl^- become concentrated in the residual water since they are not transferred by ET (Simpson and Herczeg, 1991, Barros et al., 2012, Vallet-Coulomb et al., 2017). However, the use of Cl^- could have uncertainties because of other potential sources such as atmospheric wet and dry deposition (Bugan et al., 2012).

Electrical conductivity, and silicon (Si) could also be used as tracers in assessing irrigation return flow. In agricultural areas, high EC values have been observed and associated with irrigation return flow containing fertilisers from crop fields (Park et al., 2018). Silica is often thought to be absent in rainfall or minimal in irrigation water, and is mobilised as water passes through the mineral soil and rocks forming the aquifer (Uhlenbrook et al., 2002, Park et al., 2018). In this regard, groundwater can have higher concentration of silica than surface water (Uhlenbrook et al., 2002). Although nitrate (NO_3^-) is rarely used as a tracer because of not being conservative (Camacho et al. 2015), it was recently used successfully by Park et al. (2018) to investigate the effects of irrigation return flow on river flows and groundwater.

2.4.3 Hydrological modelling for understanding climatic-landscape-hydrological interactions

Several hydrological models exist, enabling the assessment of the climate-water interactions at various spatial and temporal scales. Among the most widely used models is the Soil and Water Assessment Tool (SWAT) (Arnold and Allen, 1999). The standard SWAT model has been used by many researchers to assess the effects of climate and landcover change on hydrology in the context of elevated CO_2 (Jha et al., 2006, Van Liew et al., 2012, Butcher et al., 2014). The plant growth module of the standard SWAT simulates ET based on CO_2 concentration effects on leaf conductance [derived from the equation by Easterling et al. (1992)]. This allows the model to be used under conditions of elevated CO_2 when modelling hydrological impacts of the future climate. The value of CO_2 in the leaf conductance equation can thus be changed from the default 330 ppm for the pre 1980s to match the CO_2 concentration for the considered study period (Butcher et al., 2014).

The challenges with many hydrological models, including SWAT, are that high quality data for a long enough period are required to calibrate and validate the models. Finding such data is often a challenge especially at meso-scale in developing countries. Also, weather data needed to initialise the models tends to be sparse and not well representative. Satellite remote sensing-based weather data is more recently helping to fill some of these data gaps.

2.4.4 Resolving the limitations in the nexus assessment methodologies

As standalone, the assessment methodologies have strengths and weaknesses in the assessment of the climatic-landscape-hydrological interactions as has been highlighted in the review. This could be improved through a framework where each method is used in the area where it has strength to generate information that could feed into the other, thereby reducing uncertainties. Additionally, improved process understanding from one assessment methodology could assist in the interpretation of the findings from the other assessment tools. The combination of statistical (PLSR), tracers-based end members mixing, hydrological (SWAT), and climatic (GCM) models can provide a powerful framework for predicting the climatic-landscape-hydrological interactions of the past, present, and future. Such an analytical framework has been proposed in Figure 1-1. The application of these techniques is the subject of subsequent chapters in the thesis.

Chapter 3

A landscape hydrology approach to inform sustainable water resource management under a changing environment: a case study for the Kaleya River Catchment, Zambia

This chapter is an edited version of:

CHISOLA, M. N., VAN DER LAAN, M. & BRISTOW, K. L. 2020. A landscape hydrology approach to inform sustainable water resource management under a changing environment: A case study for the Kaleya River Catchment, Zambia. *Journal of Hydrology: Regional Studies*, 32, 100762. https://doi.org/10.1016/j.ejrh.2020.100762

Abstract

The ability of a landscape hydrology approach to detect controls on water availability in a fragmented landscape to inform interventions under a changing environment was investigated. Simple and measurable climatic and landscape pattern attributes were analysed using change detection, trend analysis and backward variable elimination with Partial Least Squares Regression (PLSR) to identify controls on seasonal river flows and how landscape components could be enhanced to augment natural river flows. Landscape pattern showed increasing fragmentation, expansion of irrigated cropland and reservoirs and loss of forestland. Significant increasing trends ($p<0.05$) were observed for evapotranspiration (ET), one-day maximum rainfall, coefficient of variation (CV) of rainfall, maximum dry spell length, and start of rains but not annual rainfall. Increased CV of rainfall, rainfall intensity and ET were the main climatic stressors on river flows than the season/annual rainfall totals. Based on the Variable Importance in Projection (VIP), results showed that patchiness of cover was more important in explaining seasonal water availability in the case study catchment than the percentage of cover type in the landscape (PLAND). The important patch metrics were the Patch Density (PD) and Largest Patch Index (LPI) of reservoirs which were the main landscape pattern stressors. However, some percentage of cover type metrics involving PLAND of irrigated cropland and reservoirs were also among the identified stressors on water availability. On the other hand, the LPI of forestland positively explained seasonal river flows. The study recommended that water resource interventions in the region must adapt more to changing seasonal rainfall characteristics than to annual rainfall totals. Additionally, regeneration of larger forest patches could improve river flows. The approach can be applied in other regions.

Keywords: landscape metrics, rainfall characteristics, landscape fragmentation, seasonal flows, Variable Importance in Projection

3.1. Introduction

Landscapes are a mosaic of many landcover types (land cover composition) with different geometric and spatial arrangements (land cover configuration). The observed hydrological signatures are a result of the linear and non-linear interaction of landscape patterns (landcover composition and configuration) with climatic variables (Hughes et al., 2014, Ekness and Randhir, 2015). Although it can be argued that the inter-relationships between landscape elements such as forest and hydrology are well known, such interactions can be more complex in the rapidly fragmenting landscapes of tropical and subtropical Africa (Malmer et al., 2010, Guzha et al., 2018).

Despite a plethora of studies investigating land use impacts on hydrological dynamics, most studies focus on landscape composition (proportion of a landcover class in the landscape). Using landscape ecology, it has been shown that processes such as runoff generation, infiltration, evapotranspiration (ET), hydrological connectivity, sediment transport and water quality are also related to landscape configuration at a watershed scale (Shi et al., 2013, Ding et al., 2016, Boongaling et al., 2018). In this regard, landscape metrics (indices of landscape pattern) developed in the field of landscape ecology are increasingly drawing scholarly attention to understand hydrological fluxes in a changing environment (Ekness, 2013, Albalawneh et al., 2015, Ding et al., 2016, Epting, 2016, Wang et al., 2020, Yu et al., 2020).

Combining hydrological modelling with multivariate statistical methods is becoming widely used in attributing land use controls on hydrological change. This combination is used because the multivariate statistical analysis helps to further identify the salient climatic and landscape patterns that cannot be identified in a hydrological modelling approach alone. On the other hand, the hydrological model allows for simulation of flows where no reliable observed streamflow data exists, and for scenarios analysis. For example, Partial Least Square Regression (PLSR) has been applied to attribute hydrological change to specific changes in land use/landcover composition using river flows and sediment data simulated by hydrological models according to various land use scenarios (Shi et al., 2013, Woldesenbet et al., 2017, Gebremicael et al., 2019). Despite this development, the underlying drivers of hydrological variability from among climate, landscape composition and configuration patterns are rarely investigated simultaneously, hence were a subject of this study.

Previous studies have mainly used simulated river flows. However, in fragmented, heterogenous and intensively managed meso-scale catchments such as the Kaleya in southern Zambia where dam management operations data does not exist, the actual hydrological signatures and processes are difficult to reproduce due to modelling and calibration uncertainties (Hughes, 2006, Hughes et al., 2014, Abbaspour et al., 2018). Hence improved understanding of how landscape patterns affect the local hydrology could provide further information for improving hydrological model simulations. Moreover, seasonal climatic characteristics in semi-arid areas like Zambia could be more important in explaining seasonal water availability than annual totals and /or land use composition alone. Thus, managing water resources under a changing environment requires information on specific climatic changes that the water resources must adapt to.

This study addresses these gaps through the lens of the landscape hydrologist. The field of landscape hydrology provides an opportunity to integrate landscape ecology and catchment hydrology (Ferguson, 1991, Schröder, 2006). Landscape hydrology deals with landscape components such as climate, land use composition and configuration, including soils, geology and topography and how their interactions affect water movement and storage in the catchment landscape (Ferguson, 1991). One of the most distinguishing features of the landscape hydrology approach is that, it considers the interactions among the landscape components and how they can be modified by human impact to better manage the water resources and the environment in general (Ferguson, 1991). Thus, it can provide a framework for informing water resource management decisions in heterogeneous and increasingly fragmented catchment landscapes under a changing climate.

The Kaleya River Catchment (Figure 3-1) in southern Zambia has undergone extensive landscape transformations since the early 1980s. The catchment hosts Zambia's oldest private-public sugarcane irrigation scheme (Akayombokwa et al., 2017). Seasonal river flows have reduced drastically in the catchment, leading to conflicts among water users. Studies have attributed deterioration of water resources in Zambia to changes in landcover composition (Sakeyo, 2008, Chomba, 2017, Muchanga et al., 2019, Tena et al., 2019). Climate change and variability are thought to be causing further stress on water resources (GRZ, 2008, Nkhuwa et al., 2013, Ngoma et al., 2017), although this has mostly not been supported by scientific evidence, as few hydrological studies have been completed (Nkhuwa et al., 2013).

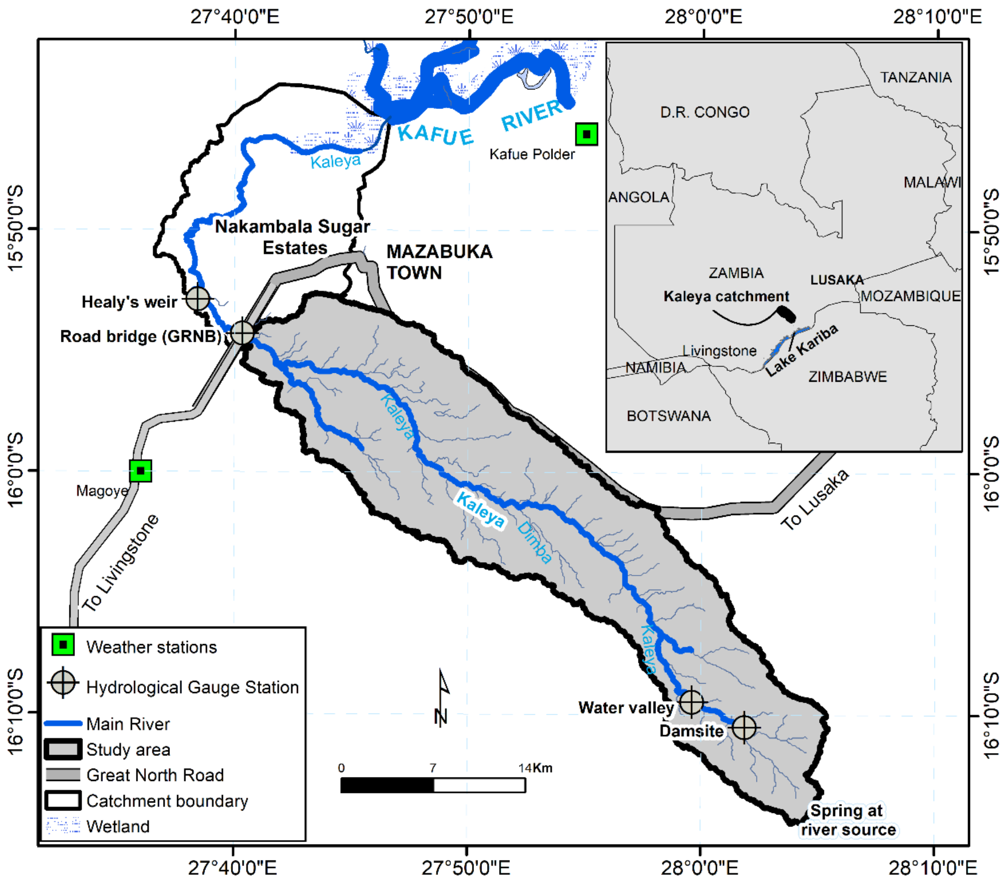


Figure 3-1: Location of river flow gauge and weather stations used in the study.

In this regard, a landscape hydrology approach was developed and tested to investigate the interactions among seasonal climatic, landcover composition and configuration patterns that explain the observed hydrological shifts in the Kaleya River Catchment. In particular, the study addresses the following research questions: (1) How have seasonal climatic characteristics and landscape patterns changed in the catchment since 1972? (2) What climatic, land use composition and configuration characteristics are important in explaining changes in seasonal river flows in the catchment? (3) How should landscape components be enhanced in order to augment seasonal river flows? (4) Can a landscape hydrology approach (implemented without hydrological simulation) detect the main interactions among landscape components to inform landscape level water resource management interventions in a heterogeneous and fragmented catchment landscape? Such information can inform improved decision-making and sustainable water resource development under a changing environment.

3.2 Materials and methods

3.2.1 The landscape hydrology approach implementation

The study uses climatic indices and landscape pattern metrics derived from long-term weather data and satellite images respectively to infer controls on seasonal river flows without need for hydrological modelling. The approach was applied using post classification landscape change detection, trend analysis of hydro-meteorological time series and variable elimination in Partial Least Squares Regression (PLSR). The details of how the approach was implemented are discussed in the subsequent sections.

3.2.2 Data acquisition and pre-processing

Cloud-free landsat images of the Kaleya River Catchment were downloaded from the website of the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov) for years 1972, 1984, 1989, 1996, 2001 and 2011. The images were pre-processed by applying geometric and radiometric corrections that included noise and haze reduction. Pre-processing also involved resampling the 60m resolution Landsat MSS image of 1972 to a 30m resolution using the nearest neighbour resampling method. All the image pre-processing steps were conducted in Erdas Imagine 2014. Historical daily river discharge data from the gauge stations (Figure 3-1) for the period 1972 to 2019 were provided by the Water Resources Management Authority

(WARMA) in Zambia. However, the dataset has gaps between 2011 and 2018, so the analysis was restricted to the 1975-2011 period which had less gaps.

Climate data were obtained from the Zambia Meteorological Department (ZMD). This data was for the Kafue polder and Magoye weather stations which are the only available weather stations around the catchment. The two datasets were averaged using the simple arithmetic mean method to get the catchment rainfall (Figure 3-2). Despite the sparse distribution of weather data within the catchment, the data from both stations was still representative of the catchment as it was able to reproduce the discharge hydrograph even for the most upstream gauge. Rainfall in the study area is seasonal such that annual rainfall is almost synonymous to seasonal rainfall totals. Dry season rainfall is very rare and minimal to significantly impact dry season streamflow (Figure 3-2).

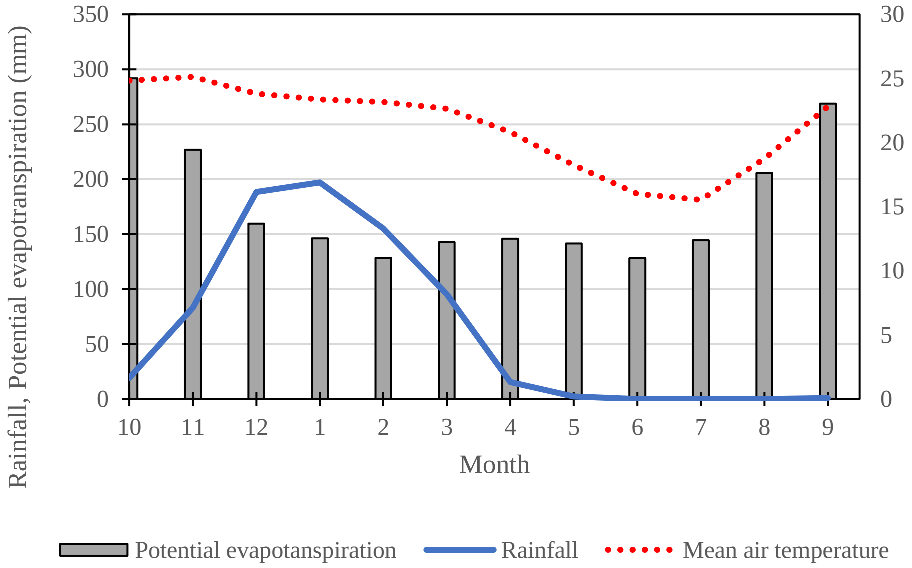


Figure 3-2: Average seasonal rainfall and potential evapotranspiration in the Kaleya River Catchment

3.3 Data analysis

3.3.1 Hydrological and climate-based metrics

The discharge data was analysed using the Indicators of Hydrological Alteration (IHA) software (The Nature Conservancy, 2009) to derive hydrological metrics that define seasonal water availability (mean monthly flows) and the timing of one-day maximum and minimum flows in the catchment for the period 1975–2011 which had less gaps in observed data. The timing of the minimum and maximum flows is critical to identifying the changes to when extreme streamflow conditions occur (Magilligan and Nislow, 2005). The date of minimum flow has implications for water availability for irrigation, but also for livestock watering, domestic water use, livelihoods and the ecological integrity especially for aquatic fauna and flora (Magilligan and Nislow, 2001, Zheng et al., 2019). Some important life-cycle phases such as reproduction for fish and other aquatic organisms may be linked to the timing of annual extremes, whereby any changes may lead to extinction of such organisms and invasive species colonisation (Magilligan and Nislow, 2005).

Since the hydrological year in the study area is counted from October to September, the period from October to April was taken as the wet season, while May to September was taken as the dry season (Figure 3-2). The climate-based metrics involved seasonal characteristics derived from daily rainfall data analysed in R-instant (Parsons et al., 2017). The derived metrics were one-day maximum rainfall, simple rainfall intensity (the ratio of total seasonal rainfall to the number of wet days in the season), onset and cessation dates of rainfall, and the maximum dry spell length (maximum dry period length) in a year and annual rainfall totals.

When deriving the climatic metrics, a rainy day was defined as having more than 0.85 mm of rainfall (Stern et al., 2006). The start (onset) of rainfall was a day after 1 October in each year that gives a total rainfall amount of 20 mm or more over a consecutive period of two days, in addition to the absence of a dry spell of 10 days or more in the next 30 days based on Stern et al. (2006). A dry spell was taken as a period with less than 5 mm of rainfall in five days, adopted from Hachigonta et al. (2008). The date of cessation of rainfall (End of rains) was taken as the last day after 25 February that accumulates a rainfall amount of 10 mm or more, adapted from Hachigonta et al. (2008) and Mupangwa et al. (2011). The study also derived evapotranspiration (ET) based on the Hargreaves method (Hargreaves, 1994) in R environment, through the SPEI package (Beguería et al., 2014). The coefficient of variation (CV) was computed as the standard deviation of rainfall divided by the average rainfall.

3.3.2. Digital image processing to derive landscape composition and configuration metrics

The Landsat images were classified using a hybrid of supervised image classification and onscreen digitising in Erdas imagine software to produce landcover maps for the years 1972, 1984, 1989, 1996, 2001 and 2011. The hybrid method involved first classifying the images with maximum likelihood classifier using supervised image classification. This was followed by onscreen digitising to correct any misclassified pixels. The hybrid method has been recommended by other scholars as it reduces misclassification errors (Herold et al., 2008, Betru et al., 2019). The generated landcover maps were then subjected to accuracy assessment.

Accuracy assessment was done using ground truth data collected from old topographic maps, and Google Earth imagery corresponding to the landcover map for each particular year (1972, 1984, 1989, 1996, 2001 and 2011). This was supplemented with field visits for better orientation with landscape features and landcover types. The ground truth data was gathered randomly for each landcover class and then compared to the classified landcover map using the overlay analysis tools in ArcMap (extract values to points tool). The resulting attribute table containing the classified values in one column and the observed (ground truth) values in the other column were then exported to excel where accuracy assessment statistics such as the overall accuracy and the kappa coefficient were computed. The landcover maps are based on six classes, namely: Forest, Scrubland, Cropland (rainfed), Cropland (irrigated), Reservoirs, and Built-up area. A description of these landcover classes is given in Table 3-1.

Table 3-1: Description of land cover classes

Landcover	Description
Forest	Land under thick vegetation cover
Scrubland	Grass with scattered trees and bushes, abandoned agricultural lands
Cropland (rainfed)	Land under rainfed agriculture
Cropland (irrigated)	Land under irrigated agriculture
Reservoirs	Land inundated by water arising from impoundments (dams and weirs)
Built-up area	Dense settlement area that can be described as urban

3.3.3. Generating landscape composition and configuration metrics from landcover maps

Landcover maps for the respective years were analysed using FRAGSTAT 4 software (McGarigal and Marks, 1995) to derive landscape composition and configuration metrics. These class level landscape pattern metrics (Table 3-2) were selected based on their use in literature, and simplicity in interpretation and application (Zhou et al., 2017).

Table 3-2: Landscape pattern metrics

Metric	Acronym	Description	Range
Percentage of Landscape	PLAND	Percentage of each landcover class in the landscape	0 - 100
Patch Density	PD	Number of patches of a landcover class per 100 ha	> 0
Largest Patch Index	LPI	Percentage of landscape covered by the largest patch of each landcover class	0 - 100

The Largest Patch Index (LPI) indicates patch dominance (McGarigal et al., 2012). The Patch Density (PD) indicates landscape fragmentation. Fragmentation and dominance-based metrics are important indicators of hydrological connectivity and ecosystem functioning (Schröder, 2006, Albalawneh et al., 2015). Hence their changes can lead to significant changes in water and nutrient cycling (Hobbs, 1993). A detailed description of the landscape metrics is given by McGarigal and Marks (1995) and McGarigal et al. (2012). A summary of all the derived hydrological, climatic and landscape indicators is given in Table 3-3.

Table 3-3: Hydro-climatic and landscape pattern metrics

Dependent variables	**Independent variables**		
Hydrological indices	**Climate indices**	**Landscape composition**	**Landscape configuration**
Wet season flows	Start of rains	PLAND of Forest land	*Fragmentation metrics*
Dry season flows	End of rains	PLAND of Rainfed cropland	PD Forest
Date of 1-day minimum flow	Maximum dry spell length	PLAND of Irrigated cropland	PD Rainfed cropland
Date of 1-day maximum flow	Rainfall amount	PLAND of Reservoirs	PD Irrigated cropland
	One-day maximum rainfall	PLAND of Scrubland	PD Reservoirs
	Rainfall intensity	PLAND of Built-up area	PD Scrubland
	CV of intra seasonal rainfall		PD Built-up area
	ET		
			Dominance metrics
			LPI Forest
			LPI Rainfed cropland
			LPI Irrigated cropland
			LPI Reservoirs
			LPI Scrubland
			LPI Built-up area

CV (Coefficient of Variation), ET (Evapotranspiration), PLAND (Percentage of Landscape area), LPI (Largest Patch Index), PD (Patch Density)

3.3.4. Analysis of trends in hydrometeorological time series

The Mann–Kendall trend test (Mann, 1945; Kendall, 1975) was conducted on seasonal climatic and hydrological variables in Table 3-3 to examine the significance of the trends in the study period. To account for serial correlation, the Modified Mann Kendall test was used by implementing the Yue and Wang (2004) variance correction technique in the *modifiedmk* R package (Patakamuri et al., 2017).

The Mann-Kendall test is given by the equation:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} Sgn\left(x_j - x_i\right) \tag{3-1}$$

where n is the number of observations, x_j and x_i are the j^{th} and i^{th} observations, respectively, and $j > i$. *Sgn* is the *sign* function between consecutive x values and is defined as:

$$\mathrm{Sgn}(x_j - x_i) = \begin{cases} +1 & ;\ x_j > x_i \\ 0 & ;\ x_j = x_i \\ -1 & ;\ x_j < x_i \end{cases} \tag{3-2}$$

The variance is defined by:

$$Var(S) = \frac{n\,(n-1)\,(2n+5) - \sum_{j=1}^{n} t_i\ i\,(i-1)(2i+5)}{18} \tag{3-3}$$

The modified variance $Var * (S)$ is:

$$Var * (S) = Var(S) \cdot \frac{n}{n*} \tag{3-4}$$

where n/n* is the correction factor.

The test statistic, *Z(c)* is computed by:

$$Z(c) = \begin{cases} \frac{S-1}{\sqrt{Var*(S)}} & , S > 0 \\ 0 & , S = 0 \\ \frac{S+1}{\sqrt{Var*(S)}} & , S < 0 \end{cases} \tag{3-5}$$

Given a significant level of α = 0.05, the null hypothesis of a non-existent trend can be accepted if -1.96 < Z(c) < 1.96, for a two-sided test.

Theil–Sen's slope estimator

The trend magnitude was evaluated using the Sen's slope estimator (Theil, 1950, Sen, 1968) which is given as:

$$\beta = Median\left(\frac{X_i - X_j}{i - j}\right) \ \forall\ j < i \qquad (3\text{-}6)$$

where, β is the slope of the trend in the time series and, X_j is the j th observation.

3.3.5. Partial least squares regression

Studies incorporating landscape composition and configuration metrics to attribute influence on hydrological components have mainly combined hydrological modelling with multiple linear regression (Ekness, 2013, Epting, 2016), pearson correlation (Chiang et al., 2019), stepwise regression (Amiri et al., 2019, Peng et al., 2019, Wang et al., 2020, Yu et al., 2020) or PLSR (Shi et al., 2013, Woldesenbet et al., 2017, Boongaling et al., 2018, Gebremicael et al., 2019) among other methods. However, previous studies did not incorporate seasonal climatic and landscape composition and configuration metrics simultaneously which could be important in informing water resources management in heterogenous landscapes under a changing environment. The independent and dependent variables for the PLSR models in this study are given in Table 3-3.

3.3.6 Justification for Partial Least Squares Regression (PLSR)

The PLSR was selected for several reasons. Firstly, there were many independent variables (landscape and climate metrics) (Table 3-3) and most of them are highly correlated with each other. The PLSR is useful when the independent variables are highly correlated and where there are more independent variables than observations (Carrascal et al., 2009, Woldesenbet et al., 2017, Boongaling et al., 2018). Secondly, given the high number of independent variables in this case, variable selection was important to identify only those that are significantly important in explaining seasonal river flows. PLSR is thus also a powerful tool for variable selection. Several methods for variable selection in PLSR are available and are discussed in detail by Mehmood et al. (2012).

Primarily, variable selection in PLSR is based on the Variable Importance in Projection (VIP), the loading weights and regression coefficients, but the VIPs are the most used (Mehmood et al., 2012). Variables with VIP > 0.8 are deemed to be significant. Variables with a VIP < 0.8 have no significant influence in the model. The higher the VIP, the more significant the variable is in explaining the dependent variable. The PLSR also gives regression coefficients whose sign indicates a positive or negative influence on the dependent variable. Thus, despite a variable having a small regression coefficient, it can be retained in the model if it has a large VIP (VIP > 0.8). Loading weights greater than a magnitude of 0.3 (irrespective of the sign) are taken to be significant and a variable can be deemed important on this basis. The sign of the loading weight indicates the direction of influence. The higher the loading weight, the larger the influence that a variable has on the respective component.

To obtain the optimum number of components and a balance between the explanatory and the predictive power of the model, cross validation is often used. In this regard, the Root Mean

Square Error of Validation (RMSEV) is used. The number of components giving the smallest value of RMSEV are selected as optimal for the model. The quality of the PLSR model is assessed using the goodness of fit (R^2), which indicates the explanatory ability of the model and the cross validated (R^2), which shows the extent to which the model can predict. A good PLSR model is one with $R^2 > 0.5$ and a cross validated (R^2) > 0.097 (Trap et al., 2013).

3.3.7 Implementation of the Partial Least Squares Regression (PLSR)

The PLSR was implemented using the 'pls' package (Mevik and Wehrens, 2007) in R software. Separate PLSR models were developed for each of the hydrological variables, that is, wet season flows, dry season flows, date of one-day maximum flow and date of one-day minimum flow. The independent variables (predictors) were all the climatic and landcover composition and configuration metrics as outlined in Table 3-3. The climatic and hydrological variables were averaged within small hydro-meteorological periods, avoiding inclusion of periods and years with data gaps to get the most out of the observed data.

The hydro-meteorological periods used were 1975–1979, 1980–1985, 1989–1994, 1995–2000, 2001–2005 and 2006–2011. Due to lack of continuous time series landcover data, the landcover map closest to each of the selected periods was used. The magnitude of landcover change within each hydro-meteorological period was assumed to be negligible. This approach has also been used in other investigations, for example Yu et al. (2020). Thus, hydro-meteorological conditions for the periods 1976–1979, 1980–1985, 1989–1994, 1995–2000, 2001–2005, 2006–2011 were assigned to the landcover data for 1972, 1984, 1989, 1996, 2001 and 2011, respectively. It can be argued that the years and periods left out due to data gaps in hydrological and weather data did not significantly impact the results since what was compared were the hydrological patterns with the corresponding climatic patterns in periods with high quality observed data.

Simulating hydrological data using a hydrological model could overcome some of the challenges in the data gaps. However, hydrological modelling has its own calibration uncertainties in this highly managed heterogenous catchment landscape due to many impoundments in the middle catchment. Hence the preference was to use observed data to answer the research questions regarding the individual role of observed seasonal climatic conditions and landscape pattern changes in explaining intra-annual water availability. In the PLSR, all the variables were standardised (scaled and mean-centred).

3.3.8 Variable selection

Variable selection was done through backward elimination (Frank, 1987, Pierna et al., 2009) in the 'plsVarSel' R package (Mehmood et al., 2012, Mehmood, 2016). The initial step involved running the PLSR with all the predictors in the model. Predictors with a VIP < 0.8 were iteratively removed from the model. The procedure was repeated until a model with an optimal R^2 and cross validated R^2 was obtained as outlined by others (Mehmood et al., 2012, Shi et al., 2013, Mehmood, 2016). In both the initial and final PLSR models, only the components giving the lowest RMSEV were retained.

3.4 Results and discussion

3.4.1. Hydro-meteorological patterns in the catchment from 1975–2011

Figure 3-3 shows patterns in climatic and hydrological time series data. Annual average rainfall exhibited a non-significant increasing trend ($p = 0.218$) over the study period in the catchment.

Previous studies in Zambia have found trends in rainfall amounts to be inconclusive with some stations showing non-significant decreasing trends (Mubanga and Umar, 2014). Additionally, the findings reveal significant increasing trends ($p < 0.05$) in one-day maximum rainfall, coefficient of variation of daily rainfall, maximum dry spell length (dry period length), temperature, and evapotranspiration (Table 3-4).

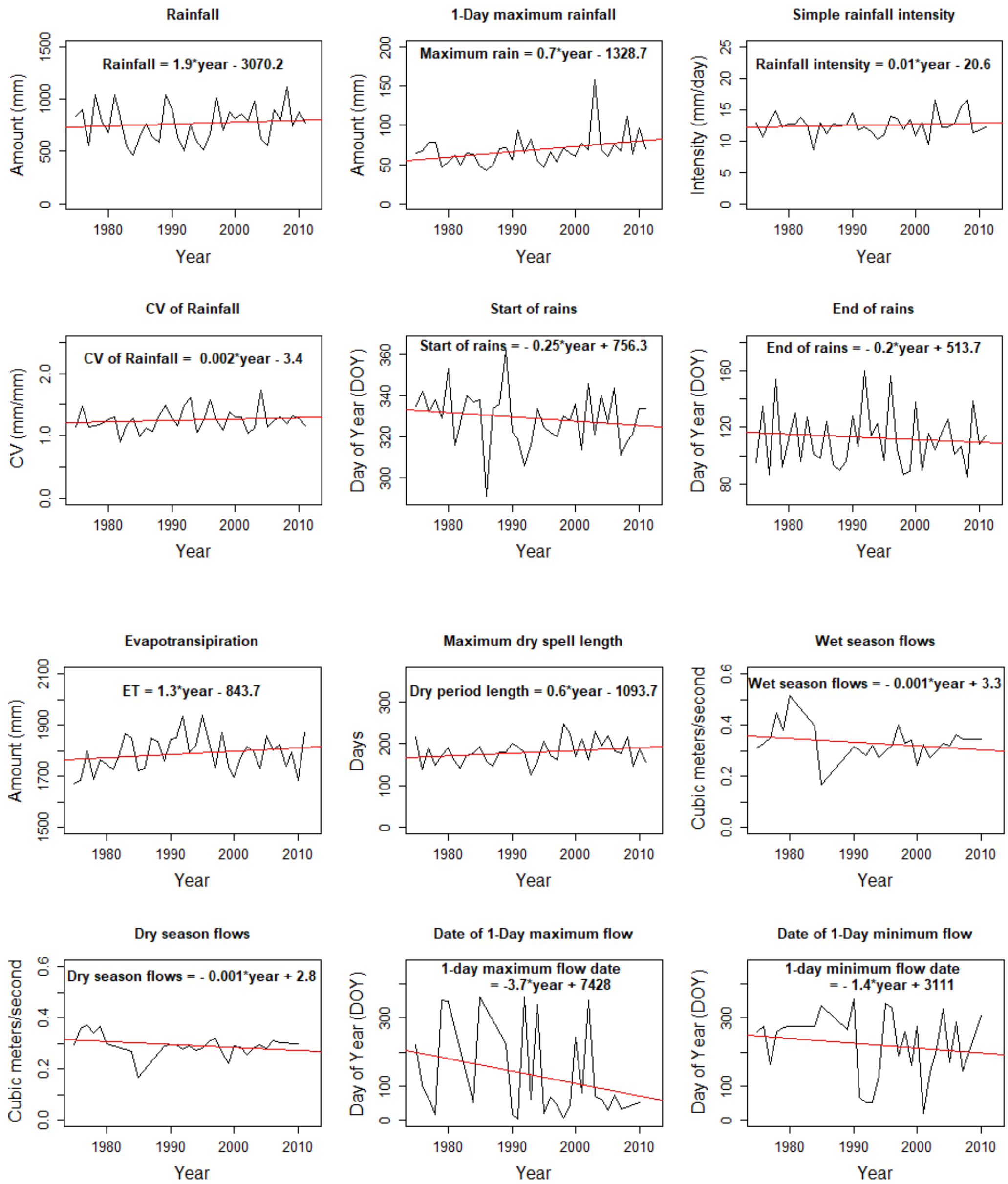


Figure 3-3: Hydro-meteorological patterns for Kaleya River Catchment in the study period

The start of the rains exhibited a significant decreasing trend ($p < 0.00$) implying earlier onset of rains. Although the early onset of rains observed in this study is contrary to the late onset that is generally reported in Zambia (Gannon et al., 2014), it is in agreement with the study by Mulenga et al. (2017), who found no evidence of later onset of rains for selected stations in Zambia contrary to the perceptions of farmers. Despite an earlier onset of rainfall, the dry spell length tended to be longer.

Table 3-4: Trends in hydro-climatic time series from 1975 - 2011 in the Kaleya Catchment

Type	Variable	Years	Zc	Sen's slope	P-value
Climatic	Temperature (˚C)	36	1.90	0.010	0.057*
	Evapotranspiration (mm)	36	2.04	1.412	0.042**
	Rainfall (mm)	36	1.23	2.078	0.218
	Start of Rains (day of year)	36	-3.59	-0.250	0.000*
	End of Rains (day of year)	36	-1.36	-0.176	0.173
	One-day Maximum rainfall (mm)	36	3.74	0.462	0.000**
	Simple rainfall intensity (mm day^{-1})	36	0.25	0.006	0.801
	CV Daily rainfall (percentage)	36	2.41	0.002	0.016**
	Maximum Dry Spell Length (days)	36	4.02	0.729	0.000**
Hydrological	Wet season flows	29	-0.57	-0.001	0.572
	Dry season flows ($m^3 s^{-1}$)	29	-1.94	-0.001	0.05**
	Date of 1-day maximum flow (day of year)	29	-1.88	-1.500	0.060*
	Date of 1-day minimum flow (day of year)	29	-0.62	-0.806	0.533

** Significant at $p < 0.05$, * Significant at $p < 0.10$

A trend implying earlier ending of the rainy season (end of rains) was observed, but it was not significant ($p = 0.17$). Mulenga et al. (2017) also found that the trends in end of rains were not significant. In the case study catchment, this decreasing trend was not significant due to greater year to year variability in cessation dates compared to the onset date. The cessation date of rainfall in southern Zambia is linked with the retreating of the Intertropical Convergence Zone (ITCZ) to the north (Hachigonta et al., 2008). Other studies have also observed a tendency towards earlier cessation of the rains even though the significance of the trends was not tested (Hachigonta et al., 2008, Gannon et al., 2014).

Regarding hydrological metrics, the results indicated significant decreasing trends in dry season flows ($p = 0.05$) and in the date when the one-day maximum flow occurs ($p < 0.10$) (Table 3-4). The decreasing trend in the timing of one-day maximum flow suggests early occurrence of the maximum flow in the river. On the other hand, non-significant decreasing trends in wet season flows and the date of one-day minimum flow were observed (earlier drying of the river), (Table 3-4). In general, the results point towards reduction in both wet and dry season river flows. In the Chongwe Catchment in Zambia, wet season flows were reported to have increased while dry season flows had declined (Chisola and Kuráž, 2016, Tena et al., 2019). In the following sections, the factors explaining the observed hydrological signatures are examined using PLSR.

3.4.2. Landscape pattern changes in the catchment

3.4.2.1. Landcover composition dynamics (Percentage of Landscape (PLAND))

Accuracy assessment conducted on the classified landcover maps showed very good classification assessment statistics. The landcover map for 1972 obtained an overall accuracy of 83% and a kappa coefficient of 0.77. The 1984 landcover map obtained an overall accuracy of 94% and a kappa coefficient of 0.92. The overall accuracy for the 1989 landcover map was 95% and a kappa coefficient of 0.93. For the 1996 landcover map, the overall accuracy was 96% and the kappa coefficient was 0.95. The 2001 landcover map obtained an overall accuracy of 94% and a kappa coefficient of 0.92. Finally, the landcover map for 2011 had a 96% overall accuracy and a 0.95 kappa coefficient. Figure 3-4 shows landcover composition from 1972 to 2011 in the Kaleya River Catchment.

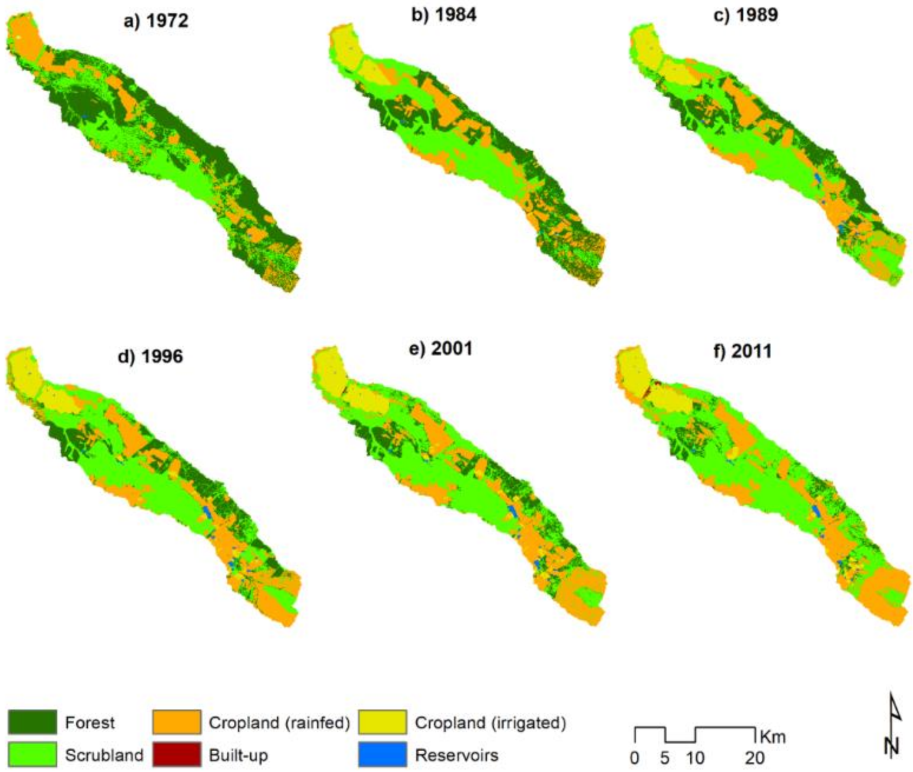


Figure 3-4: Landcover maps for Kaleya River Catchment

There is a notable reduction in forest cover and an increase in both irrigated and rainfed agricultural land (Figure 3-4). It is noted that rainfed agriculture was already a major economic activity by 1972, accounting for 21% of the landscape (Table 3-5) and was the third most dominant landcover after forest (44%) and scrubland (35%). In 2011, rainfed agriculture increased up to 33% and irrigated agriculture was at 11% (Table 3-5). Thus agriculture (both rainfed and irrigated) accounted for a total of 44% of the landscape in 2011, while scrubland dominated the landscape at about 48%.

3.4.2.2. Trends in landcover conversions in the catchment

It is noted from Figure 3-4b that irrigated agriculture had a significant presence in the lower catchment by 1984. Results further indicate that most of the rainfed agriculture land was lost to irrigated agriculture especially between 1972 and 1984 (Table 3-6, Table 3-7, and Figure 3-4). The drastic increase in irrigated land during this period is attributed to the expansion of the Nakambala Sugar Estates in to the Kaleya River Catchment, and the subsequent engagement of communities and commercial farmers through a small-holder out-grower scheme called Kaleya small holders which became operational in the early 1980s (Akayombokwa et al., 2017). This private-public partnership was aimed at increasing sugar production for exports (Akayombokwa et al., 2017).

Since 1984, expansion in irrigated land has mainly occurred from the middle portion of the catchment (Figure 3-4c-f). Table 3-7 shows that between 1972 and 2011, irrigated agriculture area gained more land from rainfed agriculture by 8% than from any other landcover class. The tendency to switch from rainfed to irrigated agriculture indicates agricultural intensification in the landscape. During the 1972–1984 period, the percentage of reservoir area increased from 0.08% (47 ha) to 0.22% (126 ha) in the landscape. This relative increase in reservoirs is much smaller compared to the dramatic increase in irrigated land from 40 ha to 4 433 ha in the same period (Table 3-5).

Table 3-5: Landcover composition (Percentage of Landscape (PLAND)) in the Kaleya River Catchment from 1972–2011

		Land use/Landcover type						
Year	**Value**	**Forest**	**Scrubland**	**Cropland (rainfed)**	**Cropland (Irrigated)**	**Reservoirs**	**Built-up**	**Total**
1972	Area (ha)	25 489	20 061	12 232	40	47	0	57 869
	Percentage (%)	44	35	21	0	0	0	100
1984	Area (ha)	17 791	21 142	14 391	4 430	115	0	57 869
	Percentage (%)	31	37	25	8	0	0	100
1989	Area (ha)	12 646	24 029	15 902	4 888	404	0	57 869
	Percentage (%)	22	42	28	8	1	0	100
1996	Area (ha)	10 129	23 811	17 654	5 809	466	0	57 869
	Percentage (%)	18	41	31	10	1	0	100
2001	Area (ha)	8 220	25 045	17 759	6 376	429	40	57 869
	Percentage (%)	14	43	31	11	1	0	100
2011	Area (ha)	4 465	27 620	18 893	6 376	384	131	57 869
	Percentage (%)	8	48	33	11	1	0	100

From inception in 1981, the Kaleya small holder irrigation scheme in the lower catchment relies on water transferred from the larger Kafue River using a 14km canal connecting to a 10km pipeline (Akayombokwa et al., 2017). The period 1984 to 1989 recorded the highest gain in the percentage of reservoirs in the landscape (Table 3-6). This was to support irrigated agriculture that was now expanding from the middle catchment, relying on water abstractions from within the Kaleya River Catchment (Figure 3-5).

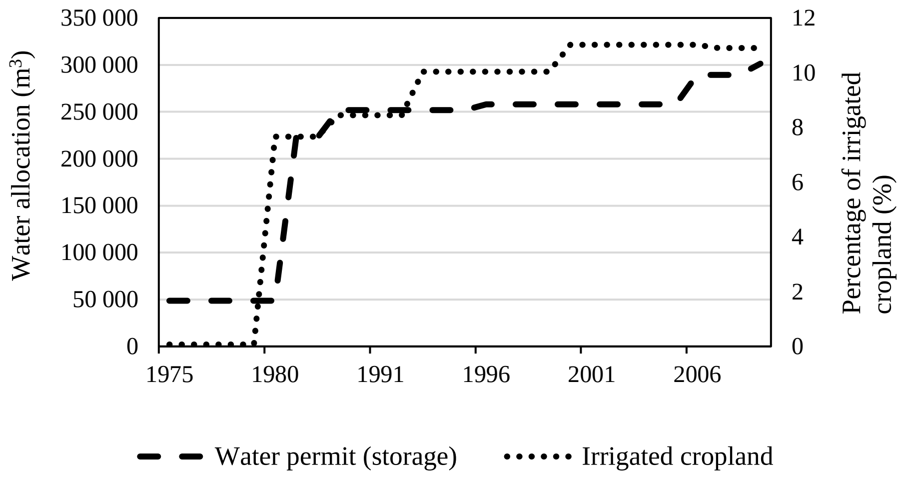


Figure 3-5: Water allocations (storage volumes) and the percentage of irrigated cropland in the Kaleya River Catchment

The lag between reservoirs and irrigated cropland from 1972–1984 and a similar pattern in their evolution afterwards is also observable from water permit data from WARMA (Figure 3-5). The net decrease in the percentage of reservoir area in the 1996–2011 period (Table 3-6) could be attributed to sedimentation, a problem that has been investigated since the late 1990s (Sichingabula, 1997, Walling et al., 2001, Sichingabula et al., 2015).

Table 3-6: Landcover change trends from 1972–2011 in the Kaleya River Catchment

Period	Statistic	Forest	Scrubland	Cropland (rainfed)	Built-up	Cropland (irrigated)	Reservoirs
1972-1984	TG (%)	6.61	12.39	13.77	0.00	7.59	0.14
	TL (%)	-19.85	-10.57	-10.09	0.00	0.00	0.00
	NC (%)	-13.24	1.82	3.68	0.00	7.59	0.14
1984-1989	TG (%)	3.49	10.89	7.66	0.00	1.01	0.50
	TL (%)	-12.41	-5.86	-5.03	0.00	-0.22	-0.02
	NC (%)	-8.92	5.02	2.63	0.00	0.79	0.48
1989-1996	TG (%)	4.15	9.38	7.41	0.00	1.75	0.16
	TL (%)	-8.53	-9.74	-4.40	0.00	-0.16	-0.02
	NC (%)	-4.38	-0.36	3.01	0.00	1.58	0.15
1996-2001	TG (%)	3.88	9.40	4.21	0.07	1.14	0.05
	TL (%)	-7.22	-7.28	-3.93	0.00	-0.15	-0.17
	NC (%)	-3.33	2.12	0.27	0.07	0.99	-0.12
2001-2011	TG (%)	2.30	11.47	6.25	0.16	1.04	0.11
	TL (%)	-8.86	-6.81	-4.33	0.00	-1.15	-0.16
	NC (%)	-6.56	4.66	1.92	0.16	-0.11	-0.06
1972-2011	TG (%)	1.51	24.64	21.72	0.23	10.83	0.60
	TL (%)	-37.95	-11.36	-10.21	0.00	0.01	-0.02
	NC (%)	-36.43	13.28	11.51	0.23	10.84	0.59

TG (Total Gain), TL (Total Loss), NC (Net Change)

The increase in irrigated land and reservoirs is expected. These trends are a response to the changing climatic patterns in addition to meet the increasing food demands. In Table 3-7, it is further observed that from 1972 to 2011 forestland has mainly been lost to scrubland and rainfed cropland [Cropland(rainfed)].

Table 3-7: Landcover change matrix comparing 1972 and 2011 landcover

	LULC	Forest (%)	Scrubland (%)	Cropland (rainfed) (%)	Built-up (%)	Cropland (irrigated) (%)	Reservoirs (%)	Total (%)
		Landcover 2011						
Landcover 1972	Cropland (irrigated) (%)					0.07		0.07
	Cropland (rainfed) (%)	0.28	1.90	11.02	0.07	7.80	0.09	21.16
	Forest (%)	6.17	22.73	13.23	0.06	1.68	0.18	44.05
	Reservoirs (%)		0.01				0.07	0.08
	Scrubland (%)	1.23	23.14	8.49	0.10	1.34	0.34	34.64
	Total (%)	7.68	47.78	32.74	0.23	10.89	0.68	100.00

3.4.2.3. Landcover configuration dynamics

3.4.2.3.1. Patch Density (PD) of landcover classes

Although about 8% of the landscape was still covered by forest in the catchment in 2011, the PD of forest showed that the remaining forest was more fragmented than before (Figure 3-6). The PD is an indicator of connectivity of the landcover class (type) in the catchment, with higher values indicative of a more fragmented or heterogeneous landcover class or landscape (Yu et al., 2020). Thus, it is possible to have two different periods with the same percentage cover for a landcover class, but the impacts on the flow regime could differ if one is more fragmented. The results show that forest had become more fragmentated, hence less hydrological connectivity in the forested land.

The higher PD of reservoirs, rainfed and irrigated agriculture in recent years reflect the increase in the number of reservoirs and crop fields in the landscape. The PD of scrubland does not show major changes during the study period. The general increase in the number of patches for all landcover types relative to the base year (1972) is consistent with the findings of Muleta and Biru (2019) in the Guder watershed in Ethiopia since 1973.

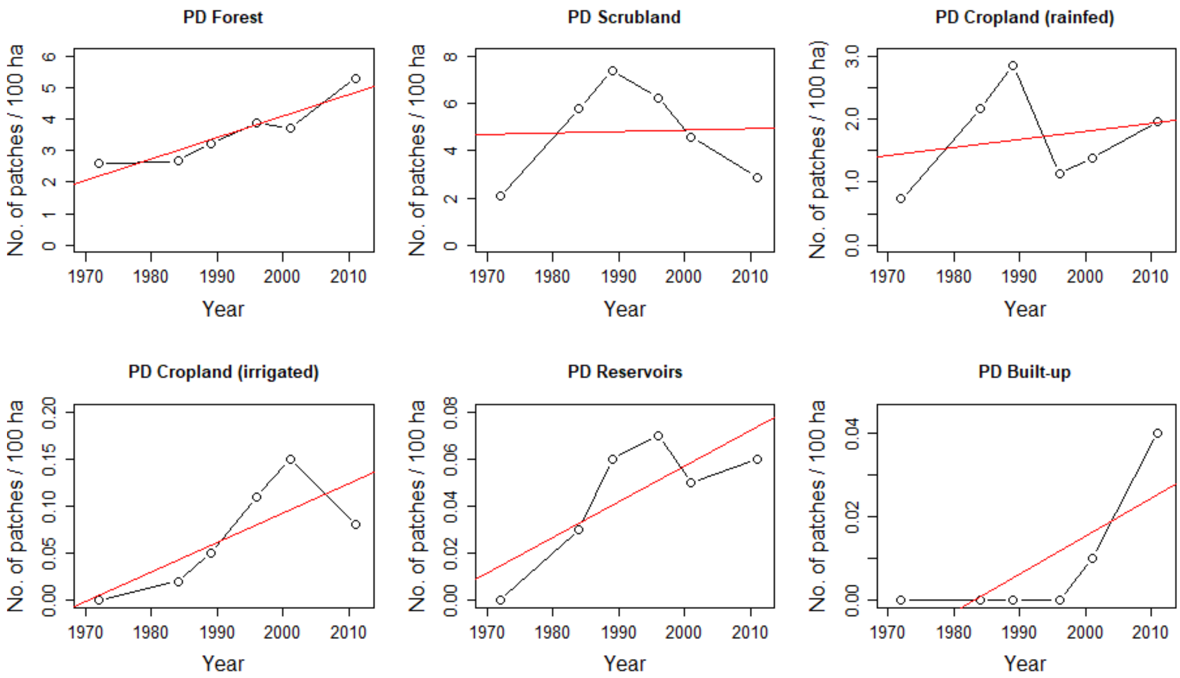


Figure 3-6: Patch density (PD) for each landcover class from 1972 to 2011 (The red line shows the direction of the trend)

3.4.2.3.2. Largest Patch Index (LPI) of landcover classes

The Largest Patch Index (LPI) is an indicator of dominance of a landcover class in the landscape. Thus, a landcover class can have a smaller percentage in terms of composition in the landscape but have a large enough patch size to influence eco-hydrological processes. The results indicate that LPI for forest has been reducing, while that of the non-forest landcover classes has been increasing (Figure 3-7).

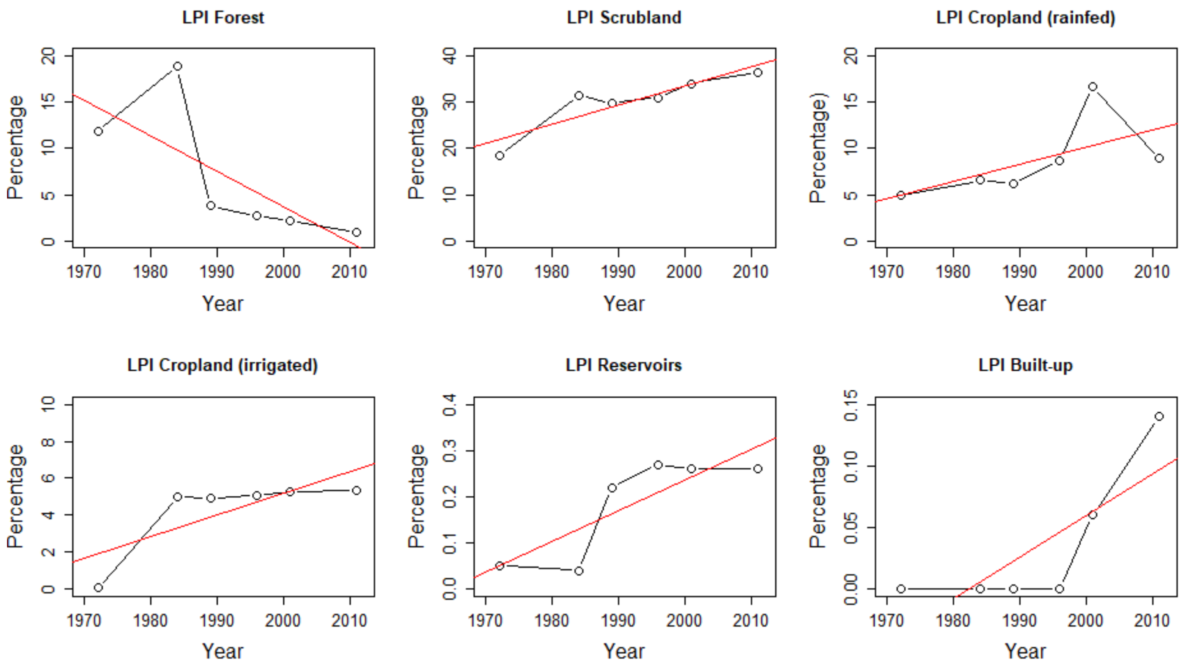


Figure 3-7: Largest patch index (LPI) per landcover class from 1972 to 2011. (The red line shows the direction of the trend)

The findings in Figure 3-7 provide further evidence of a more fragmented and scattered forest landscape and the increasing dominance and connectivity of scrubland, rainfed and irrigated cropland. Before 1984, there were smaller reservoirs and weirs in the landscape. Since then, bigger reservoirs such as the Kaleya Dam have been constructed, thus explaining the increasing LPI for reservoirs. The LPI value for the built-up area is increasing showing that the built-up area is becoming more compact. Similar trends with respect to decreasing LPI of forests, and increasing LPI of reservoirs and built-up areas were observed by Wang et al. (2020) in the Danjiangkou Reservoir Catchment in China. Hydrologically, the changes in PD and LPI affect the travel times and the timing of extreme river flows such as the date of maximum and minimum flows in the catchment.

3.4.3. Attributing river flows to seasonal climatic conditions and landscape dynamics

3.4.3.1. Wet season flows

The PLSR model for wet season flows had one component explaining 77% of the variance in the predictors. The R^2 for the model was 0.84 and the cross validated R^2 was 0.64. The major factors explaining the decreasing wet season flows were landscape based, mainly dominated by reservoir metrics, particularly patch metrics (Table 3-8). These include the percentage of reservoirs (PLAND Reservoirs), along with the largest patch areas of reservoirs (LPI Reservoirs) and patch density of reservoirs (PD Reservoirs) in the landscape. These interacted with climate metrics involving evapotranspiration (ET) and variability of rainfall (CV rainfall) to explain decreasing wet season flows.

Higher density of reservoirs (PD reservoirs) increases catchment fragmentation (Chin et al., 2008), and thus reduces landscape connectivity. By impounding the river water, downstream wet season flows are reduced while evaporation losses increase especially in the face of rising temperatures. Reservoirs amplify the negative effects of increasing variability of rainfall, thereby reducing downstream wet season flows. Thus, although reservoirs are touted as an adaptation intervention to rainfall variability and or climate change, there effectiveness remains uncertain. Research questions on this subject have revolved around what reservoir capacity, numbers, and density are optimal to build resilience (Chin et al., 2008, Ehsani et al., 2017). This could also be a question for further research in Kaleya Catchment.

Among the important variables explaining wet season flows, only the size of forest patches (LPI Forest) and the onset date of rains (start of rains) had positive regression coefficients, thus indicating their positive contribution in explaining wet season flows. Generally, larger forest patches reduce direct runoff and soil erosion, but increase groundwater recharge and baseflow (Boongaling et al., 2018, Zong et al., 2020). Promoting larger forest patches in the Kaleya catchment landscape could therefore improve infiltration and baseflow opportunities and reduce direct runoff and sedimentation. This could in turn improve water availability as the upstream catchment is groundwater/baseflow dominated (over 50% of water is from the spring and subsurface flow in the rainy season. Groundwater/baseflow (subsurface return flow) contribution increases to 100% in the dry season, (Chapter four).

3.4.3.2. Dry season flows

The PLSR model for dry season flows improved with two components, which explained a cumulative total of 98.7% of the variance in the predictors. The model had an R^2 of 0.89 and a cross validation R^2 of 0.58. Again, the landscape-based metrics dominated the model (Table 3-8). For dry season flows, the most important (significant) variables were irrigated cropland metrics involving the percentage of irrigated cropland (PLAND Crop (irrigated)) and the large patch areas of the irrigated crop fields (LPI Crop (irrigated)). These along with the extent of the largest scrubland patches (LPI Scrubland) had negative regression coefficients explaining a decrease in dry season flows.

The dominance of scrubland reduces baseflow/ground water contribution to dry season flows due to reduced infiltrated water. On the other hand, larger patches of irrigated cropland (larger LPI Crop (irrigated)) and the increase in the percentage of irrigated cropland in general (PLAND Crop (irrigated)) explained the decline in dry season flows due to water abstraction. These findings are supported by water permit allocation data which shows a very similar pattern (Figure 3-5). Thus, allocated water permit data show a strong correlation with PLAND

Crop (irrigated) (r = 0.93, $p < 0.00$) and LPI Crop (irrigated) (r = 0.89, $p < 0.00$), which have been identified by the PLSR as major stressors on dry season flows in the catchment.

Table 3-8: Partial Least Square Regression for dry and wet season flows

	Wet season flow			Dry season flow			
	VIP	Coefficients	Component 1	VIP	Coefficients	Component 1	Component 2
CV seasonal Rainfall	0.94	-0.004	-0.27				
ET	0.93	-0.004	**-0.33**				
Start of Rains	0.96	0.004	**0.40**				
PLAND Reservoirs	1.09	-0.005	**-0.42**				
PD Reservoirs	1.02	-0.004	**-0.40**				
LPI Forest	1.00	0.004	**0.40**				
LPI Reservoirs	1.04	-0.004	**-0.42**				
Rainfall Intensity				0.95	0.017	0.16	**0.91**
PLAND Crop (irrigated)				0.95	-0.006	**-0.58**	**0.30**
LPI Scrubland				0.98	-0.008	**-0.58**	0.27
LPI Crop (irrigated)				1.11	-0.011	**-0.61**	0.10

CV (Coefficient of variation), ET (Evapotranspiration), PLAND (Percentage of Landscape), (PD (Patch Density), LPI (Largest Patch Index). Loading weights in bold are significant (>0.3) on the components

3.4.3.3. Date of one-day maximum flows

The model for date of one-day maximum flows had one component explaining 82.80 % of the variance in the predictors. The R^2 was 0.83 while the cross validation R^2 was 0.44. The results indicate that the tendency towards early date of one-day maximum flow is explained mainly by climatic conditions involving higher rainfall intensities (rainfall intensity) and the earlier onset of rains (start of rains) (Table 3-9). The results further indicate that larger forest patches (larger LPI Forest) are associated with the delay in the timing of one-day maximum flow.

The results are expected as higher rainfall intensities promote quicker concentration of surface runoff on the landscape, which could contribute to early occurrence of maximum river flows. In contrast, increasing the size of forest patches (larger LPI Forest) in the landscape promotes infiltration and slows the movement of surface runoff. Hence the positive effect of larger forest patches (LPI Forest), which explains delay in the date of one-day maximum flows. However, the LPI of forest in the catchment has undergone a rapid decline over the years as observed in Figure 3-7. Hence, high rainfall intensities and decreasing dominance of forest patches (LPI Forest) are among the underlying factors explaining reduced infiltration opportunities in the catchment, and thus a tendency towards an earlier date (earlier day of the year value for one-day maximum flows) of maximum flow.

Table 3-9: Partial Least Square Regression for date of one-day minimum and maximum flows

	Date of 1-day maximum flow			Date of 1-day minimum flow		
Variable	VIP	Coefficients	Component 1	VIP	Coefficients	Component 1
Rainfall Intensity	0.91	-16.84	**-0.53**			
Start of Rains	1.08	20.08	**0.59**			
LPI Forest	1.01	18.74	**0.61**			
CV seasonal Rainfall				1.23	-17.38	**-0.57**
PLAND Reservoirs				0.87	-12.26	**-0.58**
LPI Forest				0.86	12.26	**0.61**

CV (Coefficient of variation), PLAND (Percentage of Landscape), LPI (Largest Patch Index). Loading weights in bold are significant (>0.3) on the components

3.4.3.4. Date of one-day minimum flows

Although the trend in the date of one-day minimum flows was not statistically significant, it was important to investigate the factors that could explain its variability. The PLSR results for the timing of extreme low flows are given in Table 3-9. The model had one component explaining 77% of the variance in the predictors. The R^2 was 0.72 and the cross validated R^2 was 0.40. Seasonal climatic factors involving higher variability of rainfall events (CV seasonal rainfall) and landscape metrics involving the percentage of reservoirs (PLAND Reservoirs) are associated with an early date of minimum flow. Again, the size of forest patches had a positive effect on the date of minimum flow. The results reaffirm that increasing the size of forest patches (larger LPI Forest) could promote baseflow, and thus delay the day of the year on which the minimum flow occurs. Delaying the date on which one-day minimum river flow occurs in the season has positive water availability implications.

3.4.3.5 Landscape configuration (patchiness) versus percentage of landscape composition of cover type

From Tables 3-8 and 3-9, it can be observed that the important factors explaining the seasonal water availability are dominated by landscape metrics related to the patchiness of cover type in the landscape. The importance of patchiness over the percentage of cover type metrics can further be inferred from the relatively higher Variable Importance in Projection (VIP) values for the patchiness metrics. In PLSR, variables with higher VIPs and coefficients are the most important in explaining the variations in the response variable (Farrés et al., 2015). But overall, the landscape-based metrics dominated the climate-based ones in the PLSR models especially for wet and dry season flows.

3.4.3.6 Seasonal climate and weather extremes versus seasonal (annual) rainfall totals

Based on the important variables explaining seasonal water availability in Tables 3-8 and Table 3-9, the most important climatic variables are related to seasonal climate and weather extremes. The annual rainfall and temperature totals had lower VIPs which were not significant, hence not part of the selected models/variables in Tables 3-8 and 3-9. This indicates that in the case study region, changes in climatic extremes, particularly rainfall intensity and variability, dry spell length and the onset and cessation of rains are more important. A given year can still record more than normal rainfall, but still result in less water availability, if the rainy season is characterised by longer dry spells or early cessation of rains.

The findings are consistent with Mulenga et al. (2017), who observed that there was a contradiction between farmers experiences of climate change effects and the results that indicate no trends in rainfall in southern Zambia where the study area is located. This is because trend analysis is usually done based on annual rainfall totals. Similarly, the seasonal forecast from Zambia Meteorological department merely focus on qualitative predictions such as normal, below normal, or above normal rainfall, and hardly focus on rainfall extremes such as dry spells and intensities. As such, farmers tend to report crop failures despite authorities describing a particular season as characterised by normal or above normal rainfall.

3.4.4. The landscape hydrology approach and implications for sustainable water resource management

Using the landscape hydrology approach, this study identified the climatic and landscape patterns important for informing water resource interventions in a heterogeneous intensively managed semi-arid catchment landscape. The climatic stressors were mainly associated with seasonal rainfall characteristics involving the start of rains, intensity, and variability in the season, and ET. These together with landscape metrics, particularly reservoir and irrigated agriculture-based expansions, explained much of the observed hydrological variability and declining seasonal water availability in the catchment.

Seasonal rainfall characteristics were more important in explaining hydrological patterns than rainfall totals as the former influence landscape hydrological processes of surface runoff generation, infiltration, soil moisture and ET dynamics. Given that most studies in southern African indicate non-significant increasing or decreasing trends in annual rainfall totals (Kusangaya et al., 2014, Mubanga and Umar, 2014, Taye et al., 2015), this study argues that it is in fact the changing seasonal rainfall distribution that must be of concern for water resources management in the region. An improved understanding of trends in seasonal rainfall characteristics such as its intensity, variability and dry spell lengths could be even more important than annual rainfall trends for developing resilience in semi-arid areas.

The findings suggest that increasing the size of forest patches could offset the negative effect of increasing rainfall intensities and dry spell lengths by helping in flood mitigation through delaying the occurrence of peak river flows and supporting dry season river flows by delaying the date of one-day minimum flow. Larger forest patches can thus be a nature-based solution to promote infiltration and baseflow. The study thus recommends increasing the percentage of forest area by promoting larger forest patches in the catchment to benefit both wet and dry season river flows.

Reforestation could be achieved through farmer-assisted natural regeneration of scrubland and abandoned rainfed agricultural land (Akinnifesi, 2018, Ndeso-Atanga, 2018) as the majority of the catchment landscape is controlled by farmers and the corporate sector. The miombo woodland which is dominant in the catchment has a good coppicing and natural regeneration potential (Luoga et al., 2004, Syampungani, 2009, Handavu et al., 2011).

Zambia’s Forest Act No. 4 of 2015 (Forest Act, 2015) provides an opportunity for farmers and the corporate sector to own forests and thus diversify their income sources through private forests. Farmers can earn additional revenues from non-timber forest products like mushrooms, honey (bee-keeping) and carbon credits while protecting and enhancing water availability for their agricultural produce. Mfune (2018) proposes the formation of forest cooperatives that can assist in increase the volumes of forest produce from individual farmers (forest patches) and enhance the negotiation power so that farmers can get the most out of their forest practices. This diversification could also buffer the farmers against climatic shocks that may affect their agricultural production.

Irrigated agriculture was an important variable explaining reduced water availability, especially during the dry season. This is due to increased abstractions and increasing ET (mainly due to increasing temperature) as shown in the results. In this regard, irrigated agriculture in the catchment should move towards more efficient systems and management practices, as well as high value crops farmed on less land.

Overall, it was notable from the research findings that landscape configuration patterns especially with respect to consolidated patches of a particular landcover type appeared to be more important in explaining hydrological dynamics. This has important implications on understanding the climatic-landscape-hydrological interactions under a changing environment given that most hydrological models rarely explicitly consider the patchiness of cover in the way they are structured. Even though parameter calibration may make up for this, in most cases it doesn't, and may thus constitute another source of uncertainty with the hydrological models.

3.4.5 Study limitations and recommendations for future research

The potential effects of different land covers on infiltration and baseflow/groundwater contributions could not be investigated. Future studies and further application of the landscape hydrology methodology developed in this study could thus quantify and use the baseflow index and water yield (streamflow/rainfall) as part of the hydrological indices. This would better assess the potential effects of forest/land use changes on infiltration and groundwater recharge in the catchment. This could also be extended to assessment of green water stocks such as soil moisture, where long term data is available.

3.5 Conclusions

A landscape hydrology approach was successfully applied without hydrological modelling in a highly managed heterogeneous catchment landscape. The approach was able to detect stressors from among the landscape components and inform water resource management interventions at a landscape scale. Significant increasing trends in seasonal climatic characteristics of ET, one-day maximum rainfall, CV of daily rainfall, and maximum dry spell length have occurred in the Kaleya River Catchment over 1975–2011 but not in total annual rainfall. In contrast, both the onset and cessation of rains show a trend towards earlier onset and cessation even though the latter was not significant. Both dry and wet season flows show declining trends, but only the former is significant.

Based on landscape composition metrics, the study concludes that there has been a dramatic decline in forested land, expansion of irrigated cropland mainly from land previously used for rainfed agriculture. There has also been increase in reservoirs and the catchment landscape is more fragmented in recent years.

The major climatic stressors on seasonal water availability are all associated with increasing ET and seasonal rainfall characteristics namely: increasing variability of rainfall, dry spell length and rainfall intensities. In this regard, water resource interventions in the region must adapt more to the changing seasonal climatic characteristics than annual totals. On the landscape side, the major stressors on water availability are the increasing percentage of reservoirs and irrigated cropland, increase in the sizes (patch metrics) of reservoirs and irrigated crop fields and increased density of reservoirs. Of these, the patchiness of a cover type metrics dominated the percentage of cover type metrics in explaining water availability.

It is recommended that more efficient agricultural water use and farmer-assisted natural regeneration of forest patches towards larger forest patch sizes is needed to enhance landscape hydrological processes that improve seasonal water availability. The approach in this study can be applied to other catchments where no major gaps exist in the time series data on climate and hydrology, and where good quality temporal landcover data is available.

In summary, chapter three focused on the climatic-landscape-hydrological interactions of the past, utilising historical observed climate, discharge, and satellite imagery (Figure 3-8). To assess the present interactions and major streamflow sources, another technique with better strength in assessing the present water use dynamics and their implications on streamflow was required. For example, in the absence of observed records on irrigation return flows, and wastewater, tracer-based techniques are required. Hence Chapter four builds on Chapter three to quantify streamflow sources in the present era of agricultural intensification.

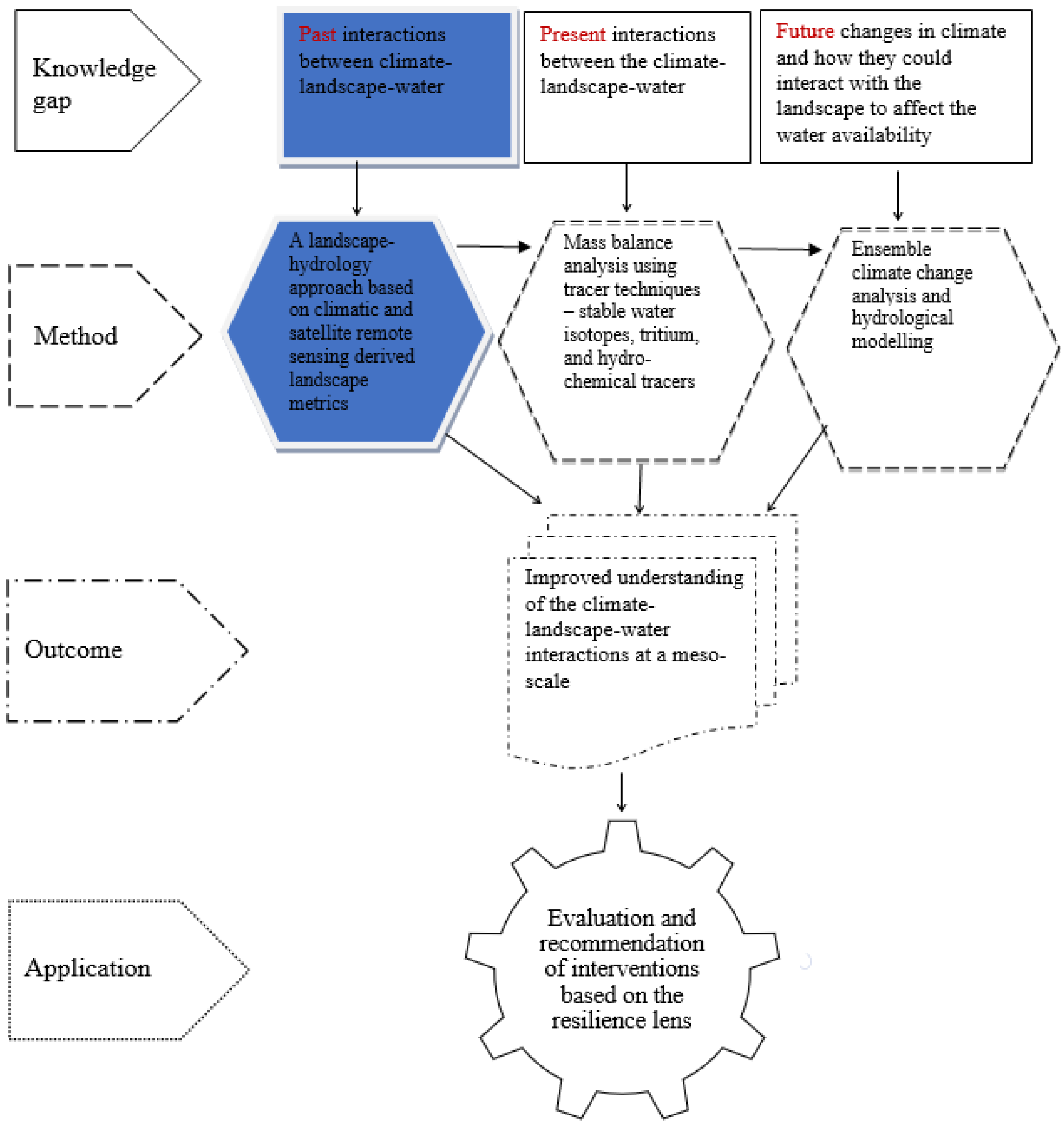


Figure 3-8: Analytical framework showing the focus for chapter three

Chapter 4

Quantifying streamflow sources to improve water allocation management in a catchment undergoing agricultural intensification

This chapter is an edited version of:

CHISOLA, M. N., VAN DER LAAN, M. & BUTLER, M. J. 2022. Quantifying streamflow sources to improve water allocation management in a catchment undergoing agricultural intensification. *Physics and Chemistry of the Earth*, Parts A/B/C, 128, 103227. https://doi.org/10.1016/j.pce.2022.103227

Abstract

Changes in streamflow contributing sources in semi-arid catchments undergoing agricultural intensification are often poorly understood. As a result, pathways to increase resilience to environmental change are not well established. Mixing model analysis using stable water isotopes and hydro-chemical tracers was applied to evaluate streamflow sources in the Kaleya Catchment, Zambia. Results showed that strong agricultural intensification signal influenced streamflow sources in time and space. In the rainy season, streamflow mainly originated from stormwater runoff from non-irrigated areas (43 ± 13) %, the perennial spring (39 ± 21) % and stormwater runoff from the irrigated areas (18 ± 17) %. But in the dry season, the spring (65 ± 15) % and irrigation return flows (35 ± 15) % became the important upstream sources, while downstream sources were irrigation return flows (73 ± 15) % and wastewater containing vinasse (27 ± 15) %, both associated with water originally transferred from the adjacent Kafue River. Given the current importance of irrigation return flows to downstream users including ecosystems, social cooperate responsibility and/or water markets must help to improve irrigation efficiency while simultaneously ensuring downstream flows are maintained.

Keywords: end member mixing analysis; intra-basin transfer water; Kaleya Catchment; stable water isotopes; wastewater; return flow

4.1 Introduction

Semi-arid areas, such as most parts of southern Africa, experience a climate characterised by distinct rainy and dry seasons. Climate change is resulting in an increased frequency of extreme events (droughts and floods) and higher rainfall intensities (Chisola et al., 2020, Nhemachena et al., 2020). Rainfall often only occurs for four to five months, so the dry season is relatively longer, placing pressure on water and food security. Irrigated agriculture intensification is often adopted in the region to increase agricultural productivity and grow export quality produce (Nhamo et al. 2019, Nhemachena et al. 2020, Hamududu and Ngoma 2020, Akayombokwa et al. 2017).

Given that most rivers and streams in meso-scale catchments are intermittent and ephemeral (Magand et al., 2020, Belemtougri et al., 2021, Fovet et al., 2021), irrigation often depends on groundwater abstractions, small dams, springs, and inter- and intra-basin water transfer schemes. Along with deforestation caused by the clearing of large tracts of land for agricultural expansion (German et al., 2020), these hydrological modifications alter the dominant runoff generation processes and streamflow sources. In many cases, this has left both water and food availability vulnerable to climatic variability and change (Misra 2014). Often there is a call to increase irrigation efficiency by reducing water ‘losses’, without properly understanding the fate of the return flows.

The water accounting concept recognises that while irrigation return flows may constitute water loss at the scale of water application, they are not necessarily losses at a river catchment scale as they may be recovered by downstream users and the riverine environment (Perry, 2007, Perry et al., 2009, Dumont et al., 2013). Case studies have highlighted the risk to downstream water availability that could arise with increased irrigation efficiency (Dumont et al., 2013, Loch and Adamson, 2015). The ‘rebound effect’ can occur when initial water savings are used to expand irrigated areas at the expense of the environment and other downstream users. Addressing this issue does not justify excessive irrigation but provides a framework to ensure that the pursuit of water conservation does not create negative externalities on downstream flows.

Understanding streamflow sources in time and space can lead to improved management of such catchments leading to their increased resilience to environmental change (Uhlenbrook et al., 2004). Unfortunately, the streamflow gauge networks needed to derive information on streamflow source dynamics tends to be sparse, especially in developing countries (Uhlenbrook et al., 2004). Tracer-based techniques such as the mixing models (Sklash et al., 1976) and End Member Mixing Analysis (EMMA) (Christophersen et al., 1990, Hooper et al., 1990, Hooper, 2003) are then essential to fill data gaps.

The application of mixing models and EMMA for process understanding in dry climates has gained momentum in recent years (Burns, 2002, Rahman et al., 2015). However, several research questions requiring the use of these tracer-based techniques in meso-scale catchments undergoing agricultural intensification remain. While rainfall-runoff processes are important in the rainy season, inter-basin water transfers and irrigation dynamics can play an important role in the dry season. Also, wastewater from urbanising areas often tends to be discharged into the same drainage systems meant for irrigation and storm water management, especially in developing countries (Tanji and Kielen 2002). Under these circumstances, the assumptions for tracer-based techniques, such as the need for tracer concentration to remain unchanged in space and time, may fail to be met (Sklash and Farvolden 1979, Hooper et al. 1990).

This study applied these tracer-based techniques spatially and seasonally to investigate streamflow source dynamics in the water-stressed Kaleya Catchment in Zambia. The specific objectives were to (1) to investigate the dominant streamflow sources in the catchment in both the rainy and dry seasons, and (2) assess the effects that the elimination of irrigation return flows could have on downstream flows.

4.2 Water use and agricultural intensification in the Kaleya River Catchment

Irrigated agriculture has been practiced in the catchment since the beginning of the 1970s. Commercial sugarcane (*Saccharum officinarum L.*) estates in the downstream parts of the catchment were developed to increase sugar production for export to European markets (Akayombokwa et al. 2017). The irrigated area and the number of dams has continued to increase in response to unreliable rainfall (Chapter three) and the need to increase income generation (Akayombokwa et al. 2017; Chisola et al. 2020).

Irrigation in the upper and middle Kaleya Catchment depends on water from within the catchment and has led to declining dry season flows in this part of the catchment (Chisola et al., 2020) as shown by Chapter three. The sugarcane estates in the downstream part of the catchment are irrigated using intra-basin transfer water (IBTW) from the Kafue River. The total irrigated area under IBWT is about 9,857 ha (Figure 4-1). The Nakambala Sugar Estate (NSE) supplies the IBTW directly to their estates and those under their out-grower scheme called the Kaleya Smallholder Company Limited (KASCOL). The water is first stored in small night storage reservoirs within the estates from which it is later channelled to irrigation canals for flood irrigation by siphoning from the canals (Akayombokwa et al., 2017). Any return flows end up in the lower Kaleya River. Consequently, the lower Kaleya River is always flowing despite the dry middle Kaleya.

The vinasse from the brewing of local beer called *Kachasu* using sugarcane molasses in the neighbouring ‘Kaleya station’ township (an informal settlement) is dumped into some of the irrigation drainage canals and reservoirs/ponds. This vinasse mixes with water leaking/overflowing from the irrigation system, forming wastewater. The wastewater also eventually drains into the Kaleya River. Water for domestic use is often from a few boreholes in the area as well as shallow hand dug wells. Pit latrines are common due to the absence of a water supply and sewerage network within the settlement. Understanding the prevailing dominant streamflow contributing sources is required to inform integrated land and water management for increased resilience of the river system.

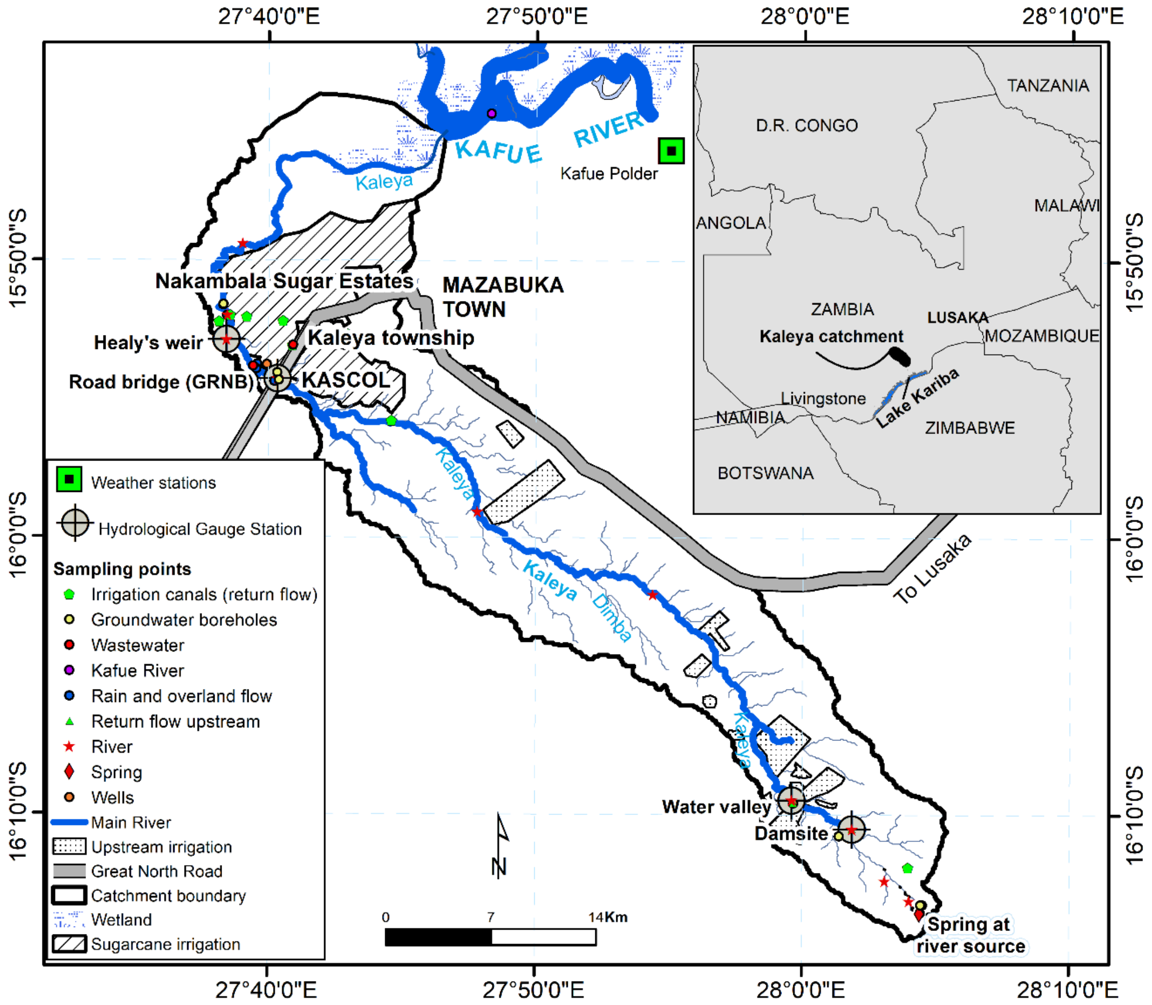


Figure 4-1: Study area with water sample locations

4.3 Materials and methods

4.3.1 Water sampling

Water sampling was informed by the findings from chapter three that highlighted the high spatial and temporal patterns of heterogeneity in the catchment. Water samples were collected between August 2019 and March 2020, covering the middle and peak of the dry and rainy seasons, respectively. In each season, each point was sampled at least twice, except for a few areas where water was found to have dried during a later sampling campaign in the dry season. Grab samples were collected from flowing water of the Kaleya and Kafue rivers, and at strategic points within the Kaleya Catchment upstream, and downstream (Figure 4-1 and Table 4-1).

Table 4-1: Sampling sites and samples

Sampling sources	**End member representation**	**Number of sites**	**Number of Rainy season samples**	**Number of Dry season samples**	**Total number of samples**
Perennial spring at river source	Spring	1	3	2	5
Boreholes irrigated areas	Groundwater (irrigated areas)	2	6	3	9
Boreholes non irrigated areas	Groundwater (non-irrigated areas)	2	4	5	9
Shallow wells (in irrigated areas)	Return flow via subsurface	2	4	4	8
Kaleya River	Streamflow	5	11	9	20
Rain/ runoff from irrigated and non-irrigated areas	Stormwater runoff	2	6	0	6
Irrigation canals	Return flow via surface flow	2	2	3	5
Drainage with wastewater	Wastewater	1	2	2	4
Kafue River at pumping site for intra-basin water transfer	Intra-basin water transfer	1	2	2	4
Total		**18**	**40**	**30**	**70**

Samples for tritium (^{3}H) analysis were collected from the spring as well as a groundwater borehole located in the upper catchment approximately 500 m downstream from the spring. Samples for stable water isotopes ($\delta\ ^{2}H$ and $\delta\ ^{18}O$) were sealed in 100ml polythene bottles, while those for physical-chemical parameters (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-1}, and SO_4^{2-}) were sealed in 1000ml polythene bottles. All samples were refrigerated for preservation. The EC, pH and water temperature were measured *in situ* using the Hanna multi-parameter meter (model: HI 9829, Hanna Instruments, Woonsocket, USA).

For streamflow, some sampling sites were located at the existing gauge stations (‘Damsite’, ‘Water valley’, ‘Road bridge’ and ‘Healys estate weir’) (Figure 4-1) to enable simultaneous recording of discharge during the time of sampling. Additionally, daily historical discharge data were obtained from 1975 - 2020 from the Water Resources Management Authority (WARMA) in Zambia. However, it had huge data gaps from 2011 - 2020. Two simple farm rain gauges were installed upstream and downstream in the catchment for rainwater sampling and measurement. For rainfall, samples were collected for each event, stored in the fridge and the total amount of water caught from various events was lumped together into one bottle to get a seasonal representative sample for each of the two rain gauge sites (one upstream, and one downstream).

The concentration of naturally occurring stable water isotopes and dissolved ions in these potential sources of streamflow tends to be different (Appendix 4-1 and Appendix 4-2). For example, irrigation return flows tends to have heavier stable water isotopes and higher concentration of ions than irrigation water. This is due to evaporation associated with irrigation as lighter isotopes are preferentially evaporated leaving behind heavier ones. In this regard, tracers involving stable water isotopes [deuterium ($\delta\ ^{2}H$) and oxygen-18 ($\delta\ ^{18}O$)] and physical-chemical parameters [calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), chloride (Cl^{-1}), and sulphates ($SO4^{2-}$)] including Electrical conductivity (EC) which have commonly been used in areas facing agricultural intensification were adopted (Simpson and Herczeg 1991, Kattan 2008, Barros et al. 2012, Vallet-Coulomb et al. 2017).

4.3.2 Laboratory analysis

Physical-chemical parameters were analysed at the Environmental Engineering Laboratory of the University of Zambia, in Lusaka, Zambia, using standard procedures for water quality analysis. Samples for $\delta\ ^{2}H$, $\delta\ ^{18}O$ and $\delta\ ^{3}H$ were analysed by the Environmental Isotope Laboratory at the iThemba LABS in Johannesburg, South Africa. For stable water isotopes, the samples were analysed using the Liquid Water Isotope Analyser [Model: LWIA-45-EP, Los Gatos Research (LGR), Mountain View, California, USA]. The isotope ratios were expressed in the delta-notation based on the formula:

$$\delta^{18}O(‰) = \left[\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{standard}} - 1 \right] \times 1000 \tag{4-1}$$

which also applies to $\delta\ ^{2}H$ ($^{2}H/^{1}H$). The delta values were expressed as per mil deviation relative to the standard mean ocean water (SMOW) for $\delta\ ^{18}O$ and $\delta\ ^{2}H$. The analytical precision was 0.5‰ for $\delta\ ^{18}O$ and 1.5‰ for $\delta\ ^{2}H$. The samples for $\delta\ ^{3}H$ were enriched by electrolysis and analysed on the Packard Tri-Carb 3170TR/SL Liquid Scintillation Counter. The detection limit for enriched samples was 0.2 Tritium Units (TU).

4.3.3 Data analysis

Both mixing model analysis (Sklash et al., 1976, Phillips and Gregg, 2001) and End Member Mixing Analysis (EMMA) (Christophersen and Hooper, 1992) were used in this study. The first step involved the determination of potential end members (streamflow sources) using

EMMA. The EMMA used more tracers to generate mixing diagrams that were used to identify streamflow sources (referred to as end members) from the wide variety of potential streamflow sources that were sampled. All the sampled endmembers were tried, but only the feasible ones were taken to the next stage and thus presented. The details on how this was done are given under section 4.3.3.1.

Once the end members were identified by EMMA, the second step used the mixing model analysis (mass balance analysis) to estimate streamflow contributions of the identified end members and the uncertainty ranges. The basis for considering uncertainties when computing mixing ratios is that the end members are usually not perfectly known. Even if the EMMA procedure identified the potential end members, their contributions to streamflow are highly variable in time and space especially in meso-scale semi-arid areas undergoing agricultural intensification (Carrera et al., 2004). Thus, the two approaches were used in a complementary way where EMMA identified the potential streamflow sources, while mixing model analysis quantified the mixing ratios of the streamflow sources and their uncertainties. The two approaches are further described in the following sections.

4.3.3.1 End Member Mixing Analysis (EMMA)

4.3.3.1.1 Bivariate and multivariate analysis of streamflow data

As a first step in EMMA, stable water isotopes ($\delta\ ^{2}H$ and $\delta\ ^{18}O$) and solutes (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-1}, and SO_4^{2-}) were examined for conservative behaviour as conservative tracers are required for EMMA. Based on Hooper (2003), the simplest approach for identifying conservative tracers is by using bivariate scatter plots. Bivariate tracer versus tracer plots were thus constructed for all solutes and stable water isotopes (Figure 4-2). The solutes and isotopes that displayed the best linear fits ($p < 0.01$) were chosen as tracers for EMMA (Hooper, 2003, James and Roulet, 2006, Correa et al., 2017).

The second step in EMMA involved determination of the dimensionality of the hydrological system through Principal Component Analysis (PCA), using the observed streamflow data for all the conservative tracers ($\delta\ ^{2}H$, $\delta\ ^{18}O$, EC, Na^{+}, and Cl^{-}). This allowed for reducing the dimension of the data by determining the number of significant principal components to retain using eigenvalue analysis. As a requirement for EMMA, the number of principal components whose eigenvalues ≥ 1, and or the number of components which cumulatively explained at least 90% of the variability in the observed streamflow data ($\delta\ ^{2}H$, $\delta\ ^{18}O$, EC, Na^{+}, and Cl^{-}) were retained (Christophersen and Hooper, 1992, Correa et al., 2017). The number of significant components was then used to determine the number of end members (streamflow sources) needed to explain streamflow sources (Christophersen and Hooper, 1992; Correa et al., 2017). Thus, based on the Rule of One (Joreskog et al. 1976), the number of end members (streamflow sources) contributing to streamflow was determined as the number of principal components retained, plus one.

4.3.3.1.2 Mixing diagrams

Having determined the number of end members through the PCA process, the final step was to identify the relevant end members. When observed data for all tracers is projected in the mixing sub space formed by the two principal components, the extreme points of the observed data that enclose the rest of the data when connected by mixing lines is what is referred to as end members (Christophersen and Hooper, 1992). Theoretically, end members are considered as sources of water that could have mixed to contribute to the observed streamflow, and thus together explain 100% of the enclosed streamflow data in a mixing diagram (Correa et al., 2017). That is, end members and principal components (principal axes) are two different things.

Thus, the mixing diagrams were constructed using the *EMMA.xls* spreadsheet program (Hooper, 2015). The standardised streamflow data for $\delta\ ^{2}H$, $\delta\ ^{18}O$, EC, Na^{+} and Cl^{-} were projected into a U-mixing space (Christophersen and Hooper, 1992), a lower dimensional space defined by PCA that describes the variability of the data (Christophersen and Hooper, 1992). The medians of all the potential end members were then orthogonally projected into the mixing subspaces of stream water samples defined by PCA.

For a three-end model, streamflow data that plotted within the triangle formed by the three end members was attributed to those end members. The streamflow data that was not enclosed by the mixing triangle were taken as resulting from other sources not accounted for in the model (Christophersen and Hooper, 1992, Pelizardi et al., 2017). For the two-end member model, streamflow values that plotted on or close to the mixing line were attributed to the respective end-end members (streamflow sources) forming the mixing line (Christophersen and Hooper, 1992, Pelizardi et al., 2017).

4.3.3.2 Mixing model analysis for computation of mixing ratios

Having determined the potential end members from the mixing diagrams, the proportion contributed by each end member and the associated uncertainties were determined using mass balance analysis. For this, the *IsoError.xls* spreadsheet program (Phillips and Gregg, 2001) was used. According to the mixing model theory, streamflow sample values are a linear mixture of the proportions of end members that form a convex polygon, where these proportions are not negative and sum up to 1. Therefore, for a three-end member mixing model, the following mass balance equations can be evaluated (Phillips and Gregg, 2001):

$$\delta J_M = f_A \delta J_A + f_B \delta J_B + f_c \delta J_C \quad (4\text{-}2)$$

$$\delta L_M = f_A \delta L_A + f_B \delta L_B + f_c \delta L_C \quad (4\text{-}3)$$

$$f_A + f_B + f_c = 1 \quad (4\text{-}4)$$

where, δJ and δL are the mean concentrations of any two different tracers (isotopic or hydro-chemical) in the streamflow mixture *M*. The subscripts *A*, *B* and *C* are the respective streamflow sources and f is the mean proportion contributed by each end member (streamflow source) to the streamflow mixture. These proportions are quantified as follows:

$$f_A = \frac{(\delta L_C - \delta L_B)(\delta J_M - \delta J_B) - (\delta J_C - \delta J_B)(\delta L_M - \delta L_B)}{(\delta L_C - \delta L_B)(\delta J_A - \delta J_B) - (\delta J_C - \delta J_B)(\delta L_A - \delta L_B)} \quad (4\text{-}5)$$

$$f_B = \frac{(\delta J_M - \delta J_C) - (\delta J_A - \delta J_C) f_A}{\delta J_B - \delta J_C} \quad (4\text{-}6)$$

$$f_c = 1 - f_A - f_B \quad (4\text{-}7)$$

Similarly, a two-end member mixing model can be evaluated using the mass balance equation (Phillips and Gregg, 2001):

$$\delta K_M = f_A \delta K_A - f_B \delta K_B \quad (4\text{-}8)$$

$$f_A + f_B = 1 \quad (4\text{-}9)$$

where, δK is the mean concentration of any tracer used, and the subscripts A and B are the respective streamflow sources. The f is the mean proportion contributed by an end member (streamflow source) to the streamflow mixture M and is computed as follows:

$$f_A = \frac{\delta K_M - \delta K_B}{\delta K_A - \delta K_B} \tag{4-10}$$

$$f_B = 1 - f_A \tag{4-11}$$

Details on how the variances and confidence intervals are calculated can be found in Phillips and Gregg (2001). Only those end member combinations that fulfilled the mixing model theory by not having negative contributions were accepted as being hydrologically plausible.

4.3.3.3 Inferring the volume of irrigation return flows from mixing model analysis

The mixing model analysis quantifies the contribution of each end member in terms of proportions. To obtain the volume of irrigation return flow in the lower Kaleya River, it was necessary to link discharge with the proportion of irrigation return flows in streamflow as determined by mixing model analysis (Equation 4-8 to 4-11), using Equation 4-12.

$$IRF = IRF\ proportion\ based\ on\ mixing\ model\ analysis\ x\ Q \tag{4-12}$$

where, IRF *is irrigation return flow and* Q is the average measured discharge of the downstream Kaleya River at Healy's estate weir gauge station.

Some of the IBTW bypasses irrigation through leakages and overflow from the system (reservoirs and canals). This water mixes with discharges from the factory and vinasse often dumped into the Kaleya drainage canal by the Kaleya community, thereby forming wastewater (Alsterhag and Petersson, 2004), as earlier discussed. The domestic waste from sewers is still negligible and difficult to account for as many households use pitlanes due to the absence of a formalised sewerage system in the area. Therefore, wastewater in this study refers to the IBTW water that bypasses irrigation through leakages and overflow from the irrigation transfer system (reservoirs and canals), mixing with water from the factory as it flows towards the Kaleya River, and carrying along with it the vinasse disposed into the canals by the Kaleya community. The proportion of this wastewater in streamflow of the downstream Kaleya, was estimated using:

$$Wastewater = Wastewater\ proportion\ from\ mixing\ model\ analysis\ x\ Q \quad (4\text{-}13)$$

4.3.3.4 Inferring age of water discharging from the spring

Tritium (^{3}H) was used to infer whether the recharge from the upstream spring is from recent precipitation or old recharge. This would assist in informing measures for sustained recharge. For this determination, ^{3}H was used. The sampling and laboratory analysis was as described under section 4.3.1 and section 4.3.2.

4.4 Results and analysis

4.4.1 Bivariate analysis

Bivariate tracer versus tracer plots showed that there was a strong positive relationship between $\delta\ ^{2}H$ and $\delta\ ^{18}O$ and between Na^{+} and Cl^{-} (Figure 4-2). Electrical conductivity also showed a relatively good relationship with stable water isotopes. Other ions such as Ca^{2+}, Mg^{2+}, and SO_4^{2-} had weaker correlations (Figure 4-2) with other potential tracers, hence were taken to have failed the conservative behaviour criteria required for EMMA. The five tracers δ ^{2}H, δ ^{18}O, EC, Na^{+} and Cl^{-} were therefore retained for further analysis with EMMA and the mixing model as they showed some linear patterns in the biplots, which suggested their conservative behaviour. Additionally, these are among the elements most used as tracers in scholarly literature (Abiye et al., 2015; Camacho et al., 2015; Kattan, 2008; Koeniger et al., 2020), hence their conservative behaviour was not unique to this study.

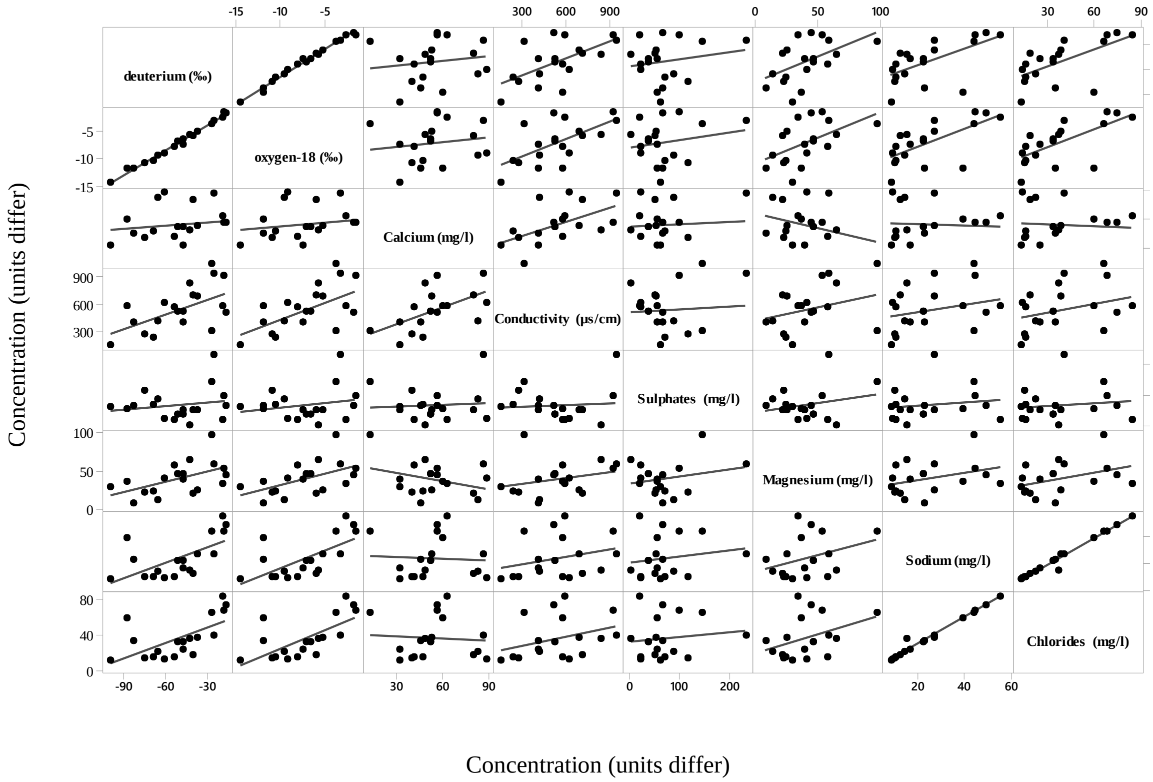


Figure 4-2: Bivariate solute plots of stream water chemistry in Kaleya catchment

Results of the PCA showed that the first two components, together explained about 92% of the variance, with eigenvalues ≥ 1 (Table 4-2). The number of principal components whose eigenvalues ≥ 1, and or the number of components which cumulatively explain at least 90 % of the variability in the observed streamflow data are usually retained in EMMA

(Christophersen and Hooper, 1992, Hooper, 2003). Based on this criteria, two principal components were retained for rainy season flows, while only one principal component was retained for dry season flows.

Table 4-2: Eigen analysis of the correlation matrix

	PC1	PC2	PC3	PC4	PC5
Eigenvalue	3.5960	0.9954	0.3972	0.0089	0.0026
Proportion	0.719	0.199	0.079	0.002	0.001
Cumulative	0.719	0.918	0.998	0.999	1.000

Table 4-3 shows that the first component was heavily weighted by stable water isotopes indicating a rainfall-runoff input, while the second component was heavily weighted by hydro-chemical tracers (EC, Na^+ and Cl^-) indicating an agricultural input (irrigation). Using the Rule of One (number of principal components retained plus one) (Joreskog et al. 1976), the results indicated that three end members (stream flows sources) would be needed to explain rainy season streamflow, while two end members would be required to account for dry season streamflow. The respective end members have been identified using mixing diagrams in Section 4.4.2.

Table 4-3: Factor loadings on the principal component analysis

Variable	Principal component 1	Principal component 2
deuterium	**0.560**	-0.439
oxygen-18	**0.579**	-0.398
Conductivity	0.420	**0.567**
Sodium	0.447	**0.510**
Chlorides	0.417	**0.572**

4.4.2 End member mixing diagrams

From the mixing diagram in Figure 4-3, stormwater runoff from non-irrigated and irrigated areas respectively and the spring were the dominant sources of streamflow in the rainy season. The stormwater runoff from non-irrigated areas was characterised by a lower EC value (6 ± 3) mS m^{-1} compared to stormwater runoff from irrigated areas (EC of (99 ± 36) mS m^{-1}) (Appendix 4-1). The stormwater runoff from irrigated areas in the downstream part was a mixture of stormwater from irrigated areas and wastewater. Hence, some rainy season upstream samples could not be enclosed in the mixing space of the three end members (Figure 4-3). Additionally, all the dry season flows upstream and downstream plotted outside the mixing space of the identified rainy season streamflow sources (Figure 4-3), indicating that these flows originate from different time and space variant sources in the catchment, which are identified in Figure 4-4.

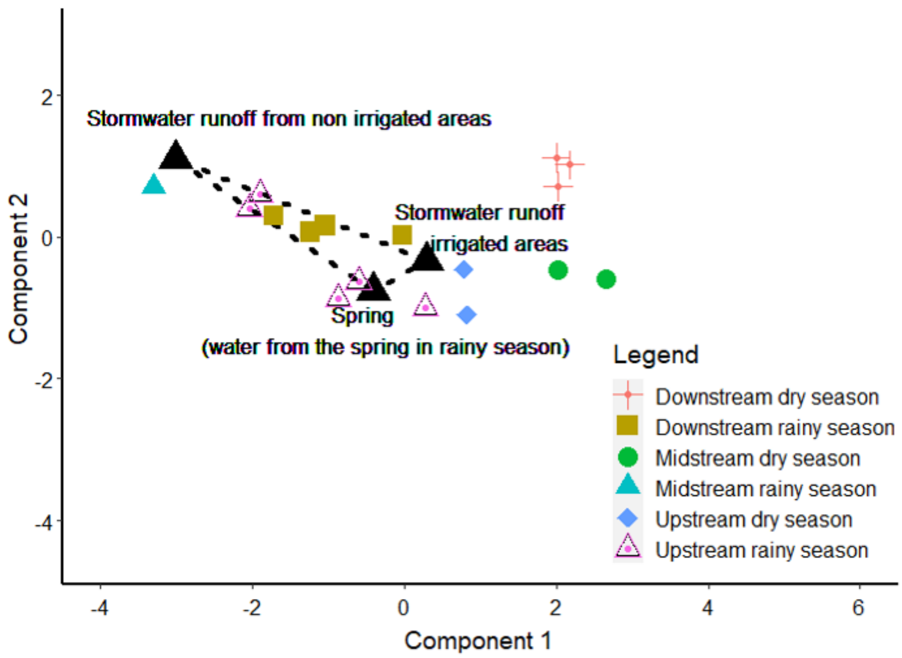


Figure 4-3: End member mixing diagram for rainy season flows (triangle) based on the first two principal components using all the conservative tracers.

Only two end members were needed to explain the dry season streamflow. Dry season flows upstream could be projected on the mixing line of the spring and the irrigation return flow end members (Figure 4-4). Hence, these were identified as upstream flow sources in the dry season. However, the downstream dry season streamflow was explained by completely different end members comprising of wastewater and irrigation return flows (Figure 4-4). The wastewater was the most enriched of all the end members in terms of the isotopic composition ($\delta\ ^{2}H$ (-17.63±1.9) ‰) and $\delta\ ^{18}O$ (-1.3±0.4) ‰) and had a relatively low EC (22.5 ± 14.8) mS m^{-1}. Additionally, the irrigation return flow in the downstream was associated with IBTW and thus differed in isotopic and hydro-chemical composition from the upstream irrigation return flow, where irrigation relied on water from within the catchment (Appendix 4-2 and Appendix 4-3).

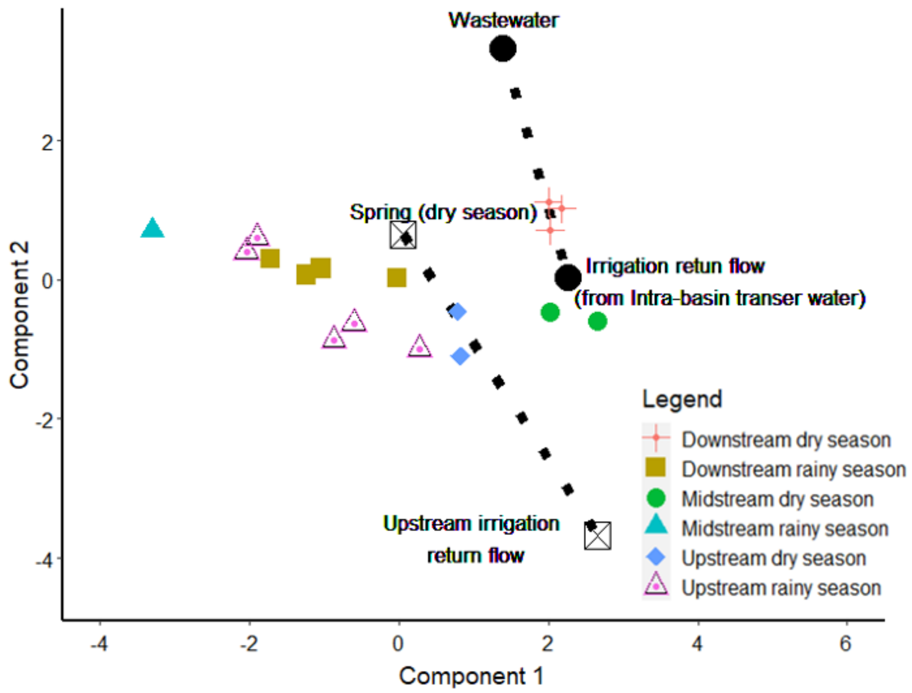


Figure 4-4: End member mixing diagrams for dry season flows (straight lines) based on the first two principal components using all the conservative tracers.

Compared to upstream, the IBTW associated return flow downstream, was more enriched in mean isotopic composition, δ ^{2}H (-18.99 ± 0.5) ‰ and δ ^{18}O (-2.34 ± 0.3) ‰. This is characteristic of the Kafue River water that is enriched in δ ^{2}H (-19.7 ± 0.5) ‰ and δ ^{18}O (-2.63 ± 0.06) ‰. Hence, the similarity in isotopic composition was not surprising because irrigation water in the lower Kaleya River Catchment is obtained from the Kafue River through transfer using a 14 km earthen canal. However, there was a notable difference between the two in terms of other parameters, especially EC, which was about (76.2 ± 33.4) mS m^{-1} in return flows compared to (28.5 ± 2.5) mS m^{-1} in irrigation water.

Since return flow upstream is associated with water from within the catchment, it had a relatively lighter isotopic composition, δ ^{2}H (-24.90 ± 8.5) ‰ and δ ^{18}O (-3.0 ± 1.6) ‰ compared to the IBTW based return flow downstream. This upstream return flow was more enriched in isotopic composition compared to the spring, δ ^{2}H (-49.0 ± 0.5) ‰ and δ ^{18}O (-7.48 ± 1.6) ‰, which contributes streamflow used for irrigation. Apart from streamflow, some of the irrigation water upstream, especially around the commercial farms, could be coming from groundwater, which had a similar isotopic composition as the spring, as well as similar EC (66.8 ± 11.5) mS m^{-1} for groundwater and (54.6 ± 11.5) mS m^{-1} for the spring. The return flow upstream was both through the surface and shallow subsurface, possibly due to the limestone/karst geology in the upper catchment. Shallow subsurface flow was observed in the Kaleya River below the earthen dam wall on the irrigated area (left bank side) at 'Water valley' road bridge. This return flow had high EC of up to 151.1 mS m^{-1}.

3.3 Quantification of mixing ratios for streamflow sources during the rainy season

The mass balance analysis based on the δ ^{18}O and EC tracers (Figure 4-5) revealed that stormwater runoff from non-irrigated areas accounted for (43 ± 13) % of the rainy season streamflow, the spring accounted for (39 ± 21) %, while stormwater runoff from irrigated areas accounted for (18 ± 17) %. The results were similar even when the δ ^{18}O and Cl^{-1} tracer combination was used, which estimated the contribution of stormwater runoff from non-irrigated areas at (48 ± 19) %, the spring at (40 ± 18) %, and stormwater runoff from irrigated areas at (12 ± 9) % of rainy season streamflow.

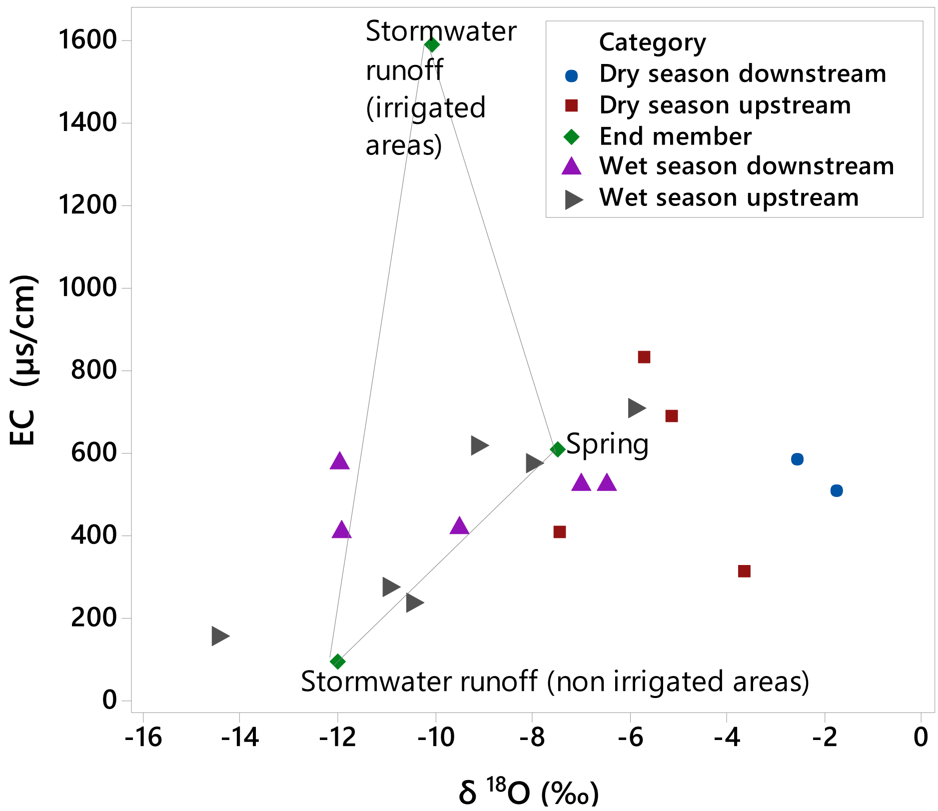


Figure 4-5: End member mixing diagram for rainy season flows based on the EC versus δ ^{18}O tracers

The mixing diagram in Figure 4-5 shows that the stormwater runoff from irrigated areas end member plotted further away from the streamflow samples in the $\delta^{18}O$ and EC mixing space. Hence this end member had the lowest contribution to streamflow compared to other endmembers. Additionally, most of the upstream streamflow samples plotted along the ‘spring – stormwater runoff from non-irrigated areas’ mixing line.

3.4 Quantification of mixing ratios of streamflow sources in the dry season

Mass balance analysis for the one end member model using EC as a tracer revealed that in the dry season, the spring directly accounted for (65 ± 15) % of the upstream river flows, while (35 ± 15) % was associated with irrigation return flows. The water from the spring is intercepted by run-on-the river dams in the upper-middle catchment, leaving downstream reaches of the river in the middle-lower catchment dry (WWF, 2018a, Chisola et al., 2020, Sichingabula et al., 2020).

The mass balance analysis (based on EC as a tracer) revealed that the downstream dry season flows are accounted for by IBTW irrigation return flows, which contributes about (73 ± 15) %, and wastewater, which contributes about (27 ± 15) %. The mixing of these end members in the $\delta^{18}O$ versus EC mixing space is indicated by the mixing line in Figure 4-6. The $\delta^{18}O$ tracer was also tested in the mass balance equation and yielded similar results, albeit with slightly larger uncertainty ranges.

The average discharge in the lower Kaleya River as recorded at Healy’s weir (Figure 1) was 0.66 m^3 s^{-1} or 57,100 m^3 day^{-1}. Based on the mixing ratio results for downstream dry season flows, the IBTW irrigation return flow contribution was estimated at about (41,683 ± 8,565) m^3 day^{-1}. The wastewater accounted for about (15,417 ± 8,565) m^3 day^{-1}.

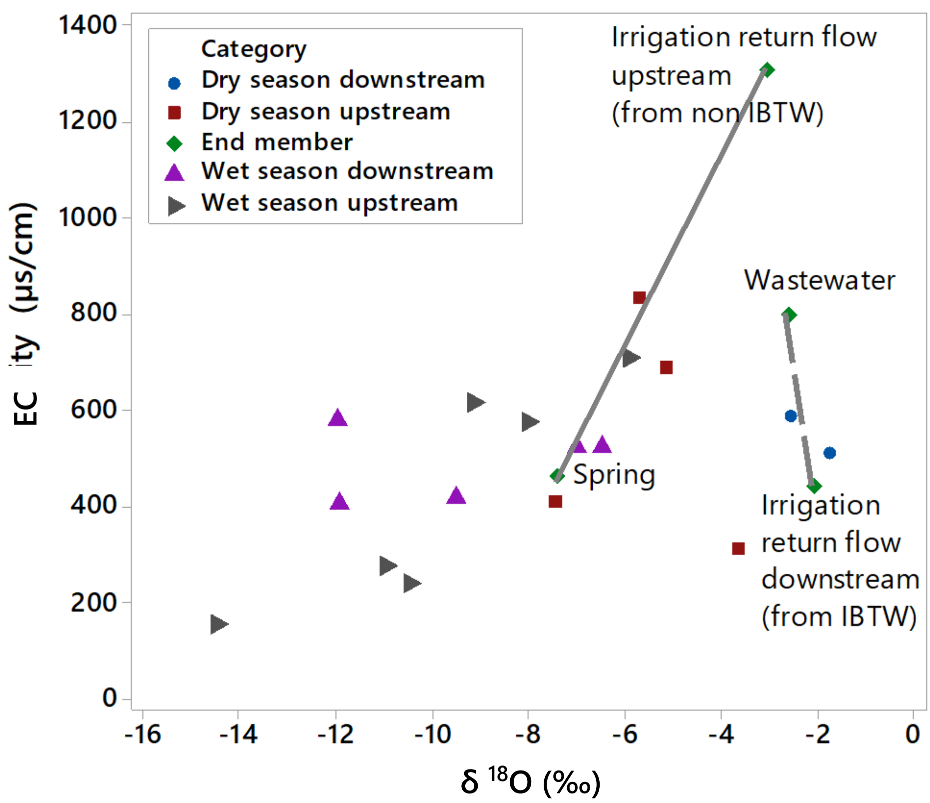


Figure 4-6: End member mixing diagrams for dry season flows based on the EC versus $\delta^{18}O$ tracers

Due to limited time series data at the catchment outlet and at Healy's estate weir, discharge at the 'Road bridge' gauge station, upstream of Healy's estate weir (Figure 4-1) was used to illustrate the varying importance of the rainfall (runoff) and agricultural input (irrigation return flow). The results were derived using the recorded discharge data at the 'Road bridge' gauge station and the mixing ratios of end members (from the mass balance analysis) during the study period. Figure 4-7 shows that the rainfall input was almost the same in magnitude as the irrigation return flow. But the importance of various streamflow sources changed in the rainy and dry seasons, with rainfall contributing to the rainy season and irrigation return flow to the dry season river flows. Sugarcane irrigation in the area mainly takes place in the dry season, hence there were negligible irrigation return flows in the rainy season.

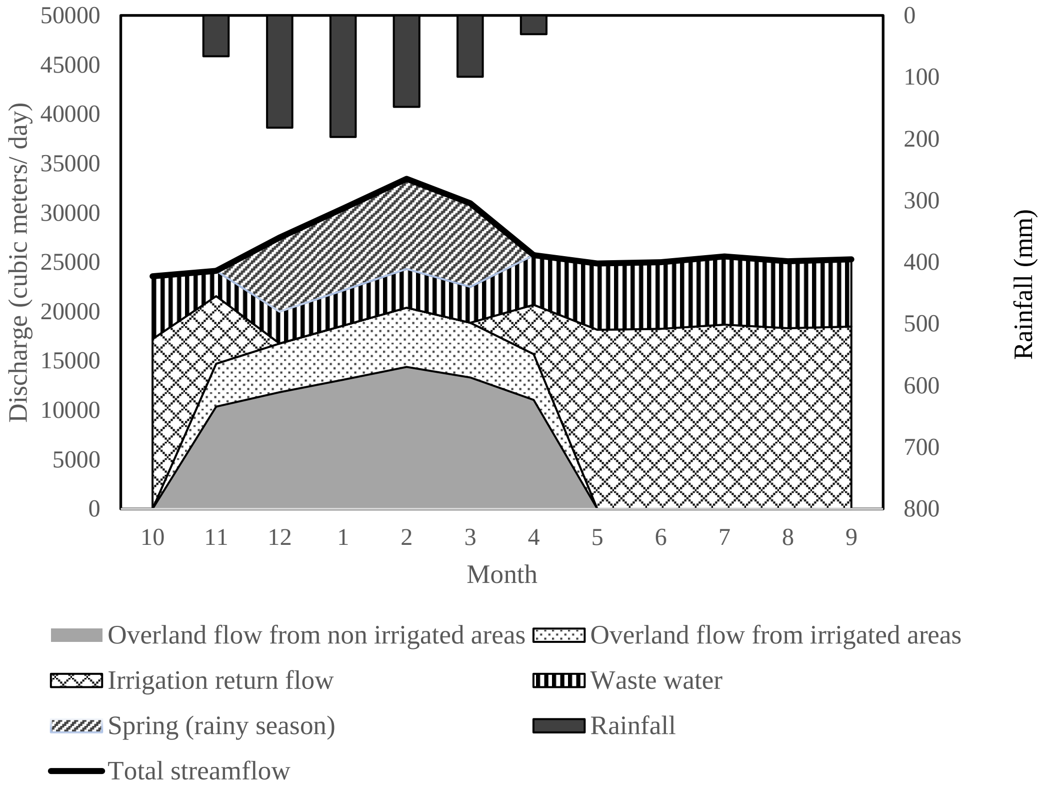


Figure 4-7: Estimated contribution of streamflow sources to mean monthly flows at Road bridge gauge station in Kaleya Catchment using mixing model analysis

3.5 Inferring the age of water from the spring in the upper catchment

Since the spring was an important source of streamflow upstream in the rainy and dry seasons, ensuring sustained recharge in the face of environmental change is needed. Hence it was important to gain insights into the age of the spring water using tritium (^3H), to infer whether this water is from recent or old recharge. Results revealed that the spring water had a ^3H value of (1.2 ± 0.3) TU, while the groundwater borehole located 500 m downstream from the spring recorded (0.4 ± 0.2) TU.

Based on Clark and Fritz (1997), water with less than 0.8 TU is considered pre-modern (at least 50 years old), while that with (0.8 – 4) TU could be considered as recent (from rainfall) mixed with old water. Based on this classification, it was determined that water from the spring is a mixture of recent and old recharge, while the groundwater downstream is predominantly old recharge. This was also corroborated by lower EC values (Appendix 4-4) for the spring (59.7 mS m^{-1}) compared to the groundwater (72.0 mS m^{-1}). This slightly lower EC for the spring could be due to constant dilution of old water with the relatively new water from rainfall. The results imply that the spring would be affected by climate and land use change effects much earlier than groundwater downstream. Measures are needed to ensure sustained recharge in the face of environmental change.

4.5 Discussion

4.5.1 Dominant streamflow sources

Given that most rivers and streams in meso-scale catchments are intermittent and ephemeral, the importance of direct runoff and the spring as natural sources of streamflow observed in this study corroborate those from other semi-arid areas in the southern Africa (Camacho et al., 2015, Mokua et al., 2020). The results also highlighted the effects of increased human activities, particularly irrigation intensification, in creating spatial – temporal differences in streamflow sources in the catchment. As such, the spring is no longer an important streamflow source downstream during low flow conditions due to the diminished hydrological connectivity caused by dams on the main river channel in the middle catchment (WWF, 2018a, Chisola et al., 2020, Sichingabula et al., 2020).

In the two years of monitoring in this study (2019 – 2020), sampling proved difficult in the middle catchment area as only pools of stagnant water in most parts of the rainy season and dry season could be observed. According to WWF (2018a), the dry state of the middle catchment was reported by catchment managers from as far back as 2015. The findings by Chisola et al. (2020) suggest that this dryness started a little earlier than 2015 and could not have been noticed by stakeholders earlier on given that the river continues to flow throughout the year in the upstream and downstream part of the catchment.

From inception, the large-scale sugarcane estates in the lower Kaleya River Catchment have irrigated using IBTW from Kafue River. The study revealed that it is the return flows and wastewater from this IBTW that are currently sustaining dry season streamflow in the downstream part of the catchment. Although out of the scope of this work, it was observed that these return flows are playing a critical role both socio-economically and ecologically. Socio-economically, the return flows are sustaining local livelihoods along the lower Kaleya by supporting gardening and other income generating activities. Ecologically, they provide an ecological flow, which often tends to be difficult to secure in meso-scale arid and semi-arid areas in the face of increasing water demand and climate change (Qureshi et al., 2010).

4.5.2 Irrigation and dry season flows in the Kaleya River Catchment

The Kaleya has two types of irrigation dynamics based on sources of irrigation water. One is in the upper and middle catchment, using water from within the catchment. The other occurs in the lower catchment using water from outside the catchment. This has been investigated in more detail in Chapter four. It has been found that the two irrigation dynamics have contrasting effects on dry season flows in the catchment. Whereas irrigation using water from within the catchment has reduced dry season flows consistent with the findings in Chapter 3 and the dry state of the middle catchment reported in this Chapter, irrigation using water from outside the catchment has increased the dry season flows (Chapter 4).

Lastly, Chapter four has also found that even within some irrigated areas using water from with the catchment in the upper catchment, there is still some irrigation return flow contribution to dry season flows. However, the dry season flows may be less than what they would be without much irrigation. As a result, the middle catchment has dried up (Chisola et al., 2020, Chisola et al., 2022).

4.5.3 Implications for management

In most IBTW schemes, water is delivered directly to the recipient river or reservoir on the recipient river (Snaddon, 1998, Purvis and Dinar, 2020). The unique characteristic of the Kaleya scheme is that it is the private commercial irrigators in the catchment who hold the permits (allocation) for IBTW instead of the catchment itself. As such, intra-basin transfer water is delivered to the sugarcane fields rather than directly to the Kaleya River. Any excess water from the irrigation activity ends up in the lower Kaleya River. Where water is not pumped directly to the recipient river, it is the sewer effluents forms of IBTW that have been reported to sustain dry season flows (Snaddon, 1998, Gupta and van der Zaag, 2008). In this regard, the findings on the important role played by the irrigation return flow associated with ‘indirect’ IBTW adds to the scholarly literature.

Over and above the socio-economic, and ecological importance, return flows associated with ‘indirect’ IBTW are often neglected in integrated water resources management, especially in meso-scale semi-arid catchments where they could be more critical. Apart from water quality concerns, return flows tend to be viewed as mere water losses, yet this is only true at field scale and may not apply at catchment scale. In this case, irrigation return flows are neither a loss at a recipient catchment scale (Kaleya) nor are they losses at the donor catchment scale (Kafue) as the Kaleya discharges back into the Kafue upstream of the IBTW pump station (Figure 4-1).

Therefore, strategies for improved water use efficiency at field application scale must be well conceived to avoid creating more negative externalities on the recipient Kaleya River Catchment. The negative externalities that could ensue include, accumulation of pollutants in the water, and/or the use of the ‘saved’ water for expansion of irrigated area or growing of other water-intensive crops (Scott et al., 2014, Berbel et al., 2018). Additionally, results have shown that if not well-planned, increasing irrigation system efficiency could result into the drying of the lower Kaleya River as well. This would have further negative consequences on the downstream users and the riverine environment. Since these enjoy priority of water allocation compared to commercial uses as espoused in the Zambian water policy and the Water Resources Management, Act No.21 of 2011 (GRZ, 2011), negative externalities need to be minimised in the interest of all.

There is a need to improve irrigation system efficiency, but also ensure that any water ‘saved’ is not used for activities that ignore the downstream and ecosystem benefits of return flows. The ‘saved’ water from IBTW could be allowed to bypass irrigation and go straight to clean the environment and provide an environmental flow. Some of this water would still end up into the ‘donor’ Kafue River downstream, where it could get more diluted and re-transferred into the Kaleya through the existing IBTW, hence recycling. Even in the current state, some of the IBTW already bypasses irrigation, but this is unintended as it is through leakages and overflow from the irrigation systems (storage reservoirs). Hence, a more effective system where flow releases are planned and controlled is proposed. This could also benefit the sugarcane estates that are often under pressure from various stakeholders and regulators of water pollution and environmental degradation (German et al., 2020).

The pumping costs could be offset using funds set aside for corporate social responsibility and environmental management given the current importance of return flows to downstream local communities and the aquatic ecosystem. Alternatively, water markets to buy off the ‘saved’ water after improving irrigation efficiency could be explored by government and stakeholders to support the continued delivery of the IBTW. Water market based initiatives are capable of addressing the current water scarcity challenges in southern Africa amid increasing and competing water demands (Matchaya et al., 2019). Elsewhere, studies have shown that such interventions can help obtain return flows for downstream uses from irrigators while promoting increased irrigation system efficiency (Qureshi et al., 2010, Grafton and Wheeler, 2018, Schwabe et al., 2020, Williams and Grafton, 2019).

For the upper catchment, ensuring sustained recharge to the perennial spring is the most sustainable way of keeping water in the catchment during the rainy season when there is surplus, for use in the dry season when there is a scarcity. This could be achieved through assisted natural regeneration of forests and other soil and water conservation practices (Chisola et al., 2020). The dams on the main river channel have impaired the downstream streamflow regime and ecology as indicated by the findings on the lack of flows in the middle catchment, and failure by the spring to contribute to downstream flows in the dry periods. Dams have not been very efficient in conserving water due to siltation and high evaporation rates (Sichingabula, 1997, Sichingabula et al., 2000a, Walling et al., 2001, Sichingabula et al., 2015). However, rather than demolish the dams as dictated by the public discourse in the area, a better option could be to construct minimum flow bypasses to always divert some flows downstream

(Habets et al., 2018). This can also help to replace some of the irrigation return flows in the lower Kaleya so that irrigation efficiency can be improved in the catchment.

4.5.4 Study limitations and future studies in the catchment

The sampling was limited by time constraints. A much longer sampling period would have been desired as it would have reduced the uncertainty ranges of the end member contributions. Despite this limitation, results are still indicative of the dominant streamflow contribution sources in the case study catchment and could still be extrapolated to catchments with similar hydro-geological settings. Future research could include a detailed study on groundwater, particularly the recharge dynamics. Thus, it is hypothesised here that the recharge zone for the spring could be the Siamakambo hills that are within 1 - 2 km upstream the spring. Given the karst environment observed in the area, water could be coming out to the surface through fractures/sink holes. The geological formation around the groundwater boreholes further downstream may not be the same as for the spring, hence the observed differences in ^{3}H.

In addition to the officially known spring (Kaleya source), there were other areas within the upper catchment where water was observed to come out of the subsurface to contribute to streamflow. This was partly tested from the point of view of irrigation return flows via the subsurface in the irrigated area upstream. But given that some streamflow samples fell outside the mixing spaces of the identified end members, it is highly likely that the subsurface discharges from the karst environment are vaster than earlier thought and are recommended for more intensive sampling in future studies. Thus, a more detailed assessment of the geology and subsurface flow pathways in the upper catchment, incorporating tracer-based techniques and groundwater modelling is thus recommended.

4.6 Conclusion

Tracer-based techniques proved useful in filling the gap of inadequate hydrological monitoring data towards improving water allocation decisions in a rapidly fragmenting landscape facing agricultural intensification. Based on the combination of EMMA and mixing model analysis, the major streamflow sources were found to reflect a strong human signal in time and space. Stormwater runoff and discharge from the spring were the important streamflow sources in the rainy season. In the absence of rainfall input in the dry season, the dams on the main river channel prevented the water from the spring higher up the catchment from reaching the lower Kaleya River. The downstream dry season flows were thus sustained by irrigation return flow and wastewater both associated with intra-basin transfer water. The results indicate that there is a need to improve hydrological connectivity and ensure that irrigation efficiency is improved in a way that will still maintain the downstream flows.

In summary, chapter four has zoomed into some of the findings of Chapter three regarding agricultural intensification and a more fragmented landscape, to better understand streamflow source dynamics in the present period (Figure 4-8). While the findings from both chapter three and four led to conclusions and recommendation for improved water allocation management under a changing environment, it remains uncertain in terms of how the future climatic-landscape-hydrological interactions would like. Hence chapter five will address this gap.

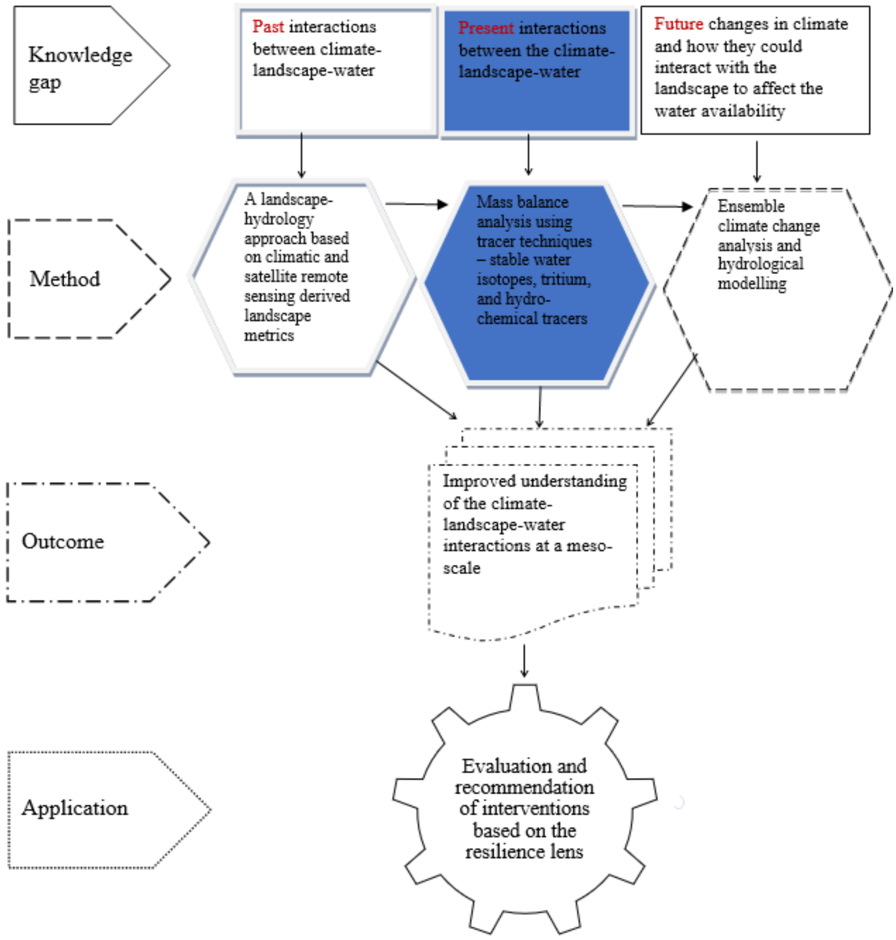


Figure 4-8: Analytical framework showing the focus for chapter four

Chapter 5

Future changes in climate and extreme weather events: implications on streamflow and sediment load

Abstract

This chapter predicted future changes in rainfall and temperatures extremes and their potential effects on streamflow, evapotranspiration, and sediment load. The meso-scale semi-arid upper Kaleya River Catchment, Zambia was used as a case study. To account for uncertainty of Global Climate Models (GCMs), two GCMs namely the MIROC5, and the MPI-ESM-LR and an ensemble (mean) prediction based on five GCMs were used. The GCMs were statistically bias corrected using the quantile mapping method for rainfall and the change factor method for temperature. The hydrological model parameter uncertainty was taken care of by calibrating the Soil and Water Assessment Tool stochastically to predict climate change impacts on hydrological components. Changes were evaluated by comparing the findings between the historical (1975 - 2005) and future period (2021 - 2050). The results indicated that the ensemble dataset predicted a 12% and 6% increase in annual rainfall under the Representative Concentration Pathway (RCP), RCP 8.5 and RCP 4.5 scenarios respectively by 2050. Annual air temperature was predicted to increase by 2˚C (RCP 8.5) and 1˚C (RCP 4.5) over the baseline. There was also a 20% (RCP 8.5) and 3% (RCP 4.5) predicted increase rainfall intensity (RX1DAY). The number of days with heavy rains (R10MM) were predicted to increase by up to 31%, while consecutive dry days [CDD (dry spells)] were predicted to increase by 1.5% under the RCP 4.5 scenario. Taking the median (M95PPU – 50% uncertainty level), the ensemble mean dataset predicted a 31% (9,675 m^3 day $^{-1}$) increase in annual streamflow under RCP 8.5, and a sediment load increase of 144% (2,175 tonnes year^{-1}). For the RCP 4.5 scenario, streamflow was predicted to increase by 21% (4,523 m^3 day $^{-1}$), accompanied by sediment load increase of 65% (994 tonnes year $^{-1}$). Annual ET was predicted to increase by 2% (9 mm) under the RCP 4.5 scenario, and no change under the RCP 8.5 scenario. While climate change could increase water availability in both the rainy and dry seasons, landcover change could reverse any potential blue water gains in the dry season and reduce green water storage by about 13%. The chapter recommends that water management interventions must view the increased rainfall amounts and intensities as a resource and target to manage the increased rainfall extremes by keeping the rainwater longer within the catchments in addition to managing sediment load.

Keywords: climate change, rainfall extremes, Global Climate Models, Representative Concentration Pathways, SWAT model, Sediment load

5.1 Introduction

Meso-scale river sub-catchments support a myriad of livelihoods and ecosystem services in sub-Saharan Africa. However, many areas in Africa have a climate that is among the most temporally and spatially variable in the world (UNFCCC, 2007, Serdeczny et al., 2017). Over the years, vulnerability to environmental change has increased the socio-climatic risks, especially among the poor in the sub-catchments of large river basins (UNFCCC, 2007, Brown et al., 2012, Serdeczny et al., 2017, Semba et al., 2020). Increasing populations, economic development, over exploitation of land resources, and agricultural intensification for local food supply and exports add to the increased vulnerability of water resources and dependent livelihoods (Hughes et al., 2015, Chisola et al., 2020).

There is thus increased demand for climate and water availability information from local to regional scale under the changing environment (Stakhiv and Stewart 2010, Hughes et al. 2015). However, only a few studies in sub-Saharan Africa have evaluated streamflow sensitivity to projected climate change in meso-scale catchments to inform planning for more climate-resilient water resources at this scale (Falkenmark and Rockström, 2010, Kusangaya et al., 2014, Theron et al., 2021). Most of the previous studies, especially in Zambia, have focused on climate change implications for hydro-electricity generation in the larger river basins (Beck and Bernauer, 2011, Yamba et al., 2011, Kling et al., 2014). But resilient meso-scale catchments are equally important in supporting local livelihoods and creating more resilient river basins beyond the local scale.

The Kaleya River Catchment in the drier southern Zambia is an example of a catchment that has continued to face agricultural intensification in the face of environmental change (Chisola et al., 2020) as shown in Chapter three and Chapter four. There has been rapid conversion of forests and scrublands to rainfed agriculture, while irrigated agriculture is taking up land previously under rainfed production in the middle and lower Kaleya River Catchment where commercial farmers are located (Chisola et al., 2020). These changes in landscape along with the changing climatic regimes have had negative impacts on streamflow and sediment load, thus reducing freshwater availability in the catchment (Sichingabula et al., 2000a, Walling et al., 2001, Chisola et al., 2020). The impacts on water availability are expected to worsen in the future as more agricultural land to feed the growing population will be needed. The climatic-landscape-hydrological interactions of the past and present have been evaluated in Chapters three and four respectively. It is however not known how future changes in climatic and weather extremes will affect water availability and sediment load in the area.

This study investigated the effects of future rainfall and temperature changes on streamflow (blue water flow), evapotranspiration (green water flow) and sediment load in the upper Kaleya River Catchment as a case study. The specific objectives were to (1) assess the plausible future changes in climate and weather extremes (rainfall, rainfall intensity, wet spell and dry spell length including daily and maximum temperature) in the catchment, (2) examine how streamflow, evapotranspiration and sediment load may respond to these changes under different climate change scenarios, (3) to evaluate how landcover change in combination with the future changes in climate may affect water availability. The findings could inform decisions towards improved adaptation to environmental change in semi-arid sub-catchments.

5.2 Study area

This chapter focussed on the upper Kaleya River Catchment to derive lessons about the effects of various climate change scenarios on hydrology and sediment dynamics. The upper catchment was used because it provided less hydrological model calibration uncertainties. It was difficult to calibrate the model at the most downstream gauge of the full catchment. This is due to the high number of reservoirs in the middle catchment that lead to no streamflow in the dry periods (Chisola et al., 2020, Chisola et al., 2022) as discussed in Chapters three and four. Data on the management of these farm reservoirs is not available. Figure 5-1 presents the study area used for this assessment.

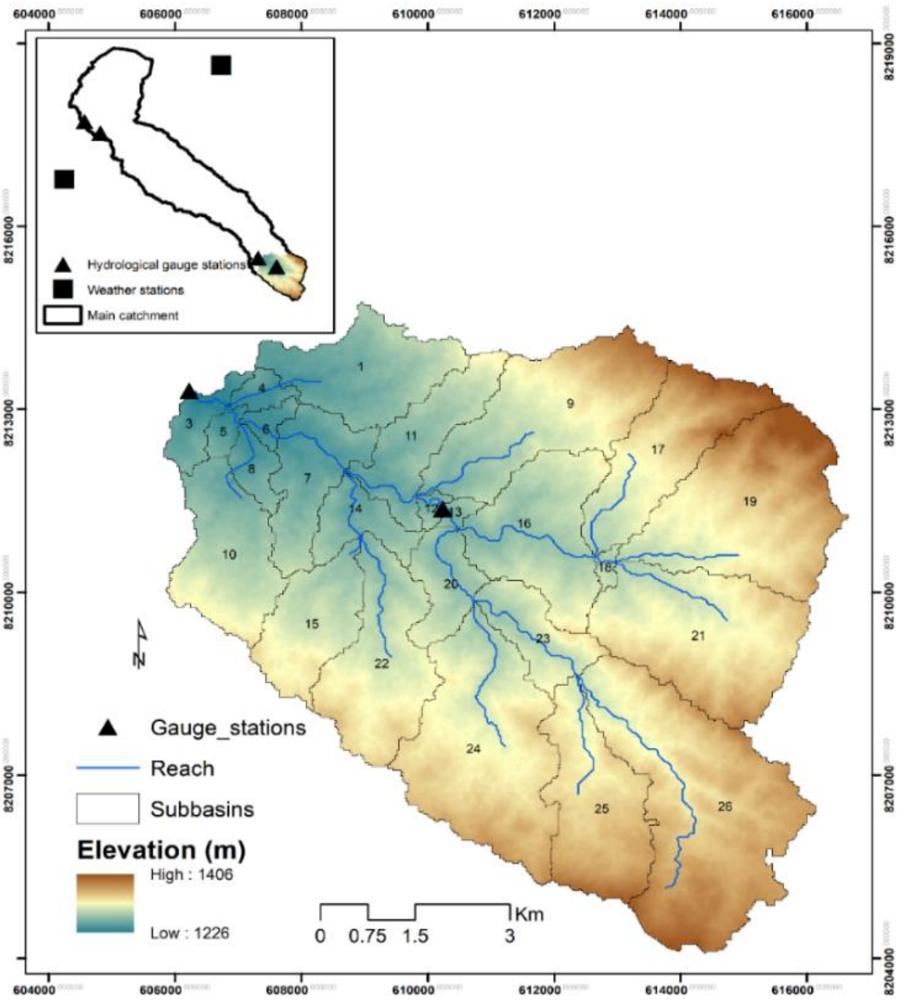


Figure 5-1: Upper Kaleya River Catchment used for model development

5.3 Materials and methods

5.3.1 Data sources and analysis

Observed rainfall and air temperature data (1975 - 2011) for Kafue Polder and Magoye meteorological stations were obtained from the Zambia Meteorological Department (ZMD). Monthly sediment load data were obtained from the Kaleya Sediment Project (Sichingabula et al., 2000b) from 1997 to 2000. The observed daily discharge data was obtained from the Water Resources Management Authority (WARMA) in Zambia. The discharge datasets were from

1975 - 2020 but had huge gaps from 2011. Hence the study used discharge data from 1975 - 2011. The historical (1975 - 2005) and projected (2021 - 2050) climate model data were obtained and downscaled from the Consultative Group on International Agricultural Research (CGIAR) programme on Climate Change, Agriculture and Food Security (CCAFS). The Global Climate Models (GCMs) were downscaled on the CCAFS-Climate portal (http://www.ccafs-climate.org/data_bias_correction/, accessed on 8th July 2021) using observed data for Kafue Polder and Magoye weather stations. The quantile mapping statistical bias correction technique was used for downscaling rainfall, while the change factor technique was used for air temperature as outlined in Navarro-Racines and Tarapues (2015).

Two climate scenarios commonly used in climate change studies, the Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios of the Intergovernmental Panel on Climate Change (IPCC) were adopted for this study as they are seen to be the most plausible. The RCP 4.5 is an intermediate scenario with a radiative forcing of 4.5 W m^{-2} and CO_2-equivalent concentration of about 650 ppm (Faggian, 2021). The RCP 8.5 is a 'business as usual' scenario, with a very high radiative forcing of 8.5 W m^{-2} arising from CO_2-equivalent concentration of about 1370 ppm (Moss et al., 2010, Faggian, 2021).

A total of 23 GCMs had data available on the CCAFS-Climate portal for both the RCP 4.5 and RCP 8.5 scenarios. Only the GCMs that had a complete baseline (historical) record (1975 - 2005) for both RCP 4.5 and 8.5 scenarios were assessed. Fewer GCMs had historical data up to 2005. The number of the GCMs was further reduced to five, based on having the highest Nash Sutcliffe Efficiency (NSE) and the Heidke Skill Score after validating the GCM data with the observed data (rainfall and air temperature). The selected five models with the highest NSE and Heidke skill score are given in Table 5-1. Projected rainfall and air temperature data were then extracted from these five downscaled GCMs under the RCP 4.5 and RCP 8.5 scenarios to get the range or envelope of possible future changes from 2021 - 2050. An ensemble mean dataset for both daily rainfall and minimum and maximum air temperature were also generated using the five selected GCMs (Table 5-1).

Table 5-1: Selected Global Climate Models with evaluation criteria

Model	Description / Modelling centre	Nash-Sutcliffe efficiency	Heide Skill Score (%)
BCC-CSM-1-1	Beijing Climate Centre, China Meteorological Administration, China	0.44	88.19
MPI-ESM-LR	Max Planck Institute for Meteorology, Germany	0.42	86.72
MPI-ESM-MR	Max Planck Institute for Meteorology, Germany	0.37	88.02
MIROC5	Model for Interdisciplinary Research on Climate, Japan	0.29	85.68
NCAR-CCSM4	National Centre for Atmospheric Research, United States of America	0.29	86.46
Ensemble mean	Average of the selected models	0.33	86.22

Measures of central tendency and selected indices explaining climatic and weather extremes were used to evaluate the climatic changes. These climatic and weather indices (Table 5-2) were computed from the World Meteorological Organization's (WMO) Expert Team on Sector-Specific Climate Indices (ET-SCI) (Alexander and Herold, 2016) CLIMPACT online portal (https://ccrc-extremes.shinyapps.io/climpact/, accessed on 11th September, 2021). The selected indices are relevant in analysing climate and weather characteristics which affect seasonal water availability and agriculture in the area (Chisola et al., 2020).

Table 5-2: Selected climatic indices used in this study

Index	Characterisation	Units
PRCPTOT	Total rainfall from wet days (rainfall ≥ 1 mm)	mm
RX1DAY	Maximum rainfall in 1 day	mm
R10MM	Number of days when rainfall ≥ 10 mm	days
CDD	Maximum number of consecutive dry days (rainfall < 1 mm)	days
CWD	Maximum number of consecutive wet days (rainfall ≥ 1 mm)	days
TMM	Mean daily air temperature	ºC
TXX	Maximum value of daily maximum air temperature	ºC

PRCPTOT - Total rainfall, RX1DAY - One-day rainfall intensity, R10MM - rainfall ≥ 10 mm, CDD - Consecutive Dry Days, CWD - Consecutive Wet Days, TMM - Mean daily air temperature and TXX - Maximum value of daily maximum air temperature (hottest day in the year)

5.3.2 Hydrological model set up

To assess the hydrological impacts of the projected climate, the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) hydrological model was developed. The datasets needed for model development included the soil data, digital elevation model (DEM), daily weather data (rainfall, minimum and maximum air temperature, relative humidity, solar radiation, and wind speed) and landcover. Observed discharge data were also needed for model calibration and validation. The sources of weather and discharge data are as described in section 5.3.1.

The soil data input to the model were based on the Zambia Soil map (GRZ, 2015). The digital elevation model was based on the 30 m resolution Shuttle Radar Topography Mission (SRTM) downloaded from the website of the United States Geological Survey (USGS) (https://earthexplorer.usgs.gov). The 1984 landcover map for Kaleya River Catchment generated by Chisola et al. (2020) as described in Chapter three was used in the model. The parameters for vegetation types were as provided in the SWAT in-built database. To match with the parameters in the SWAT database, the landcover map was reclassified with the aid of a look up table. Vegetation was reclassified to Mixed Forest (FRST), scrubland to Range-Grasses (RNGE), rainfed agriculture to Agricultural Land-Row Crops (AGRR), Irrigated agriculture to Wheat/Soyabeans (rotation), and reservoir areas to water (WATR).

During the SWAT hydrological model set-up, reservoirs were included in the model and their parameters such as the year of construction, their principal and emergency surface areas and volumes were specified. The reservoir surface areas and construction dates were based on the satellite image estimates in Chapter three. The reservoir volumes were estimated as a function of their remote sensing based surface areas (Chapter three) using equation 5-1 proposed by Sichingabula et al. (2015).

$$\textit{Reservoir volume } (m^3) = 0.7267 \textit{ x reservoir surface area } (m^2)^{1.1064}. \qquad (5\text{-}1)$$

Irrigation was included in the model through the auto-irrigation command. The source of irrigation water was set to be reservoirs for wheat and soyabeans crops that are grown in the upper catchment by commercial farmers. The model had 26 subbasins and 226 hydrological response units (hrus). The simulations were done at a monthly time-step.

5.3.3 Hydrological model calibration considerations for improving model performance

The model was developed and calibrated for the upper catchment where the uncertainties are lesser to better capture the hydrological processes. To further reduce uncertainties associated with the observed discharge data given the influence of weirs and dams even in this part of the catchment, it was necessary to calibrate the ET as well. Since there were no field based ET data available, ET data was derived using remote sensing based on the MOD16A2GF product of the Moderate Resolution Imaging Spectroradiometer (MODIS), which was available from

2000 to 2020. This data was obtained at (https://lpdaac.usgs.gov/products/mod16a2gfv061/ accessed on 27th November 2021) for the catchment and processed to generate a monthly time step series used for calibration and validation. Thus, the variables that were calibrated were streamflow, actual evapotranspiration (ET) and sediment load.

The premium version of the SWAT Calibration Uncertainties Program (SWAT-CUP Premium) was downloaded from https://www.2w2e.com/home/SwatCupPremium, accessed on 8th April 2021. It was used for model calibration, validation, uncertainty, and scenario analysis using the SWAT Parameter Estimation (SPE) algorithm. The license for SWAT-CUP Premium was purchased from the SWAT-CUP developers and included a parallel processing authorisation.

The default (uncalibrated model) had a problem of over predicting the peaks and under predicting the low flows. This informed the choice of the calibration parameters to use based on the recommendations by Abbaspour et al. (2015). The recommended parameters that were not sensitive following sensitivity analysis (one-at a time sensitivity analysis initially) were removed to avoid over parameterising the model. Hence only the most sensitive parameters were used, and these are presented in Tables 5-3 and 5-4. The final selected parameters and their sensitivities (global sensitivity in the end) after 500 simulation runs are given in Table 5-4. During calibration, the choice of the initial parameter ranges was informed by the general ranges in literature alongside the absolute ranges permissible in SWAT/SWAT-CUP. The final parameter ranges were determined by SWAT-CUP in the final iteration.

Additionally, the tracer-based study in Chapter four also provided insights about the hydrology of the study area. In particular, the dolomitic nature of the upper catchment was considered through the groundwater parameters and their ranges. The importance of the spring was considered by adding it as a point source with constant discharge, to make up for some of the unaccounted-for low flows after model calibration.

Table 5-3: Calibration parameters used and their ranges

Parameter Name	Description	Default value	Fitted Value	Initial range		Final range	
				Min value	Max value	Min value	Max value
Streamflow, evapotranspiration and sediment							
V__CH_K2.rte	Effective hydraulic conductivity in main channel alluvium	0	249.5	35	150	141	351
R__CN2.mgt	SCS runoff curve number	73 - 92	-0.1325	-0.15	0	-0.2	-0.05
R__SOL_AWC(..).sol	Available water capacity of the soil layer	varies	0.114	0	0.6	-0.06	0.3
V__GWQMN.gw	Threshold depth of water in shallow aquifer for return flow to occur (mm)	1000	188.375	0	500	10	247.83
V__REVAPMN.gw	Threshold depth of water in the shallow aquifer for “revap”to occur (mm	750	331.683	0	600	161	700
V__GW_REVAP.gw	Groundwater “revap” coefficient	0.02	0.03634	0.02	0.07	0.0251	0.1
V__RCHRG_DP.gw	Deep aquifer recharge	0.05	0.18417	0.1	0.25	0.15	0.2
V__GW_DELAY.gw	Groundwater delay (days)	31	370.5	200	430	90	420
R__SOL_BD(..).sol	Moist bulk density	varies	-0.2418	-0.2	0	-0.33	-0.1
Sediment only							
V__CH_N2.rte	Manning's "n" value for the main channel	0.014	0.29253	-0.01	0.2	0.28	0.30
V__USLE_P.mgt	USLE equation support practice factor	1	1.5755	0	1	0	0.04
V__PRF_BSN.bsn	Peak rate adjustment factor for sediment routing in the main channel	1	0.002	0	1	1.102647	1.68

V __ means the existing (or default) parameter value was replaced by a given value,

R__ means an existing (default) parameter value was multiplied by (1+ a given value)

A stochastic modelling perspective (Abbaspour, 2022) for model evaluation and analysis was adopted, rather than the deterministic perspective. To calibrate the model stochastically, two metrics called the *p-factor* and *r-factor* (Abbaspour et al., 2018, Abbaspour, 2022) were used. The *p-factor* is the percentage of the observed data that is enveloped by the uncertainty band (called 95PPU) (Abbaspour et al., 2018, Abbaspour, 2022). It thus gives the proportion of observed data that is explained by the model within its uncertainty ranges (Abbaspour et al., 2018). A *p-factor* close to 1 indicates a perfect model skill. The *r-factor* is the average thickness of the 95PPU uncertainty band. The bigger the model *r-factor* is, the larger the model uncertainty. A model having a *p-factor* > 0.7 and the *r-factor* ≤ 1.5 is recommended for discharge calibration and validation, while for sediment and nutrient loads, *p-factor* ≥ 0.4 and *r-factor* ≤ 3 could be acceptable (Abbaspour et al., 2015, Abbaspour, 2022). In this study, the *p-factor*, *r-factor*, and the Nash Sutcliffe Efficiency (NSE) were used as targets for the objective function.

5.3.4 Analysis of climate change impacts on hydrology and sediment load

After the SWAT model was calibrated and validated using observed weather and discharge data, the calibrated model was then used to assess climate change impacts. This was achieved by running the model using the historical and projected GCM weather data. However, only precipitation, minimum and maximum temperature GCM data was available. The effects of other variables such as solar radiation, wind and humidity was neglected and held constant due to lack of future Global Climate Model (GCM) data for these variables in the case study catchment at the time of analysis.

Evaluation of future climate change impacts was based on the 'one factor at a time' approach. It involved changing one factor at a time (weather data - rainfall, minimum and maximum air temperature), while keeping the other factors constant (soil, landcover, DEM, solar radiation, wind, and humidity). Climatic impacts were evaluated using the *MPI-ESM-LR* GCM model (since it showed trends consistent with observed rainfall) and the *MIROC5* GCM model (the only model that showed an opposite trend in rainfall under the RCP 4.5 scenario from among the five selected models). The ensemble (mean) dataset from the selected five best GCMs (Table 5-1) was also used for scenario development and further assessment. The climate impacts were evaluated under both the RCP 4.5 and RCP 8.5 scenarios by comparing the results between the historical and future periods. By evaluating the future climatic impacts on hydrology using the selected models and their ensemble, the GCM structural model uncertainty was considered.

To propagate the hydrological model parameter uncertainty, scenario analysis was implemented within the SWAT-CUP premium programme as opposed to writing the fitted parameters back to SWAT and running the scenarios in the standard SWAT. Apart from its use for calibrating the SWAT models, SWAT-CUP can be used to evaluate various scenarios while propagating the hydrological model parameter uncertainty through the final calibration parameter ranges. This is a stochastic perspective to the analysis (Abbaspour et al., 2018, Abbaspour, 2022). In this study, all the three levels of hydrological model parameter uncertainty with respect to the 95PPU band were calculated for each simulation. Hence the results are presented at the 2.5% (L95PPU), 50% (M95PPU) and 97.5% (U95PPU) uncertainty levels. However, given the large number of scenarios, only the results at the 50% uncertainty level (M95PPU), which is also seen as the median are further analysed and discussed.

5.3.5 Assessing the separate and combined effects of landcover and climate change

Effects of landcover change were evaluated by comparing modelling results under the 1984 landcover map representing the baseline (1970–2005) and the 2019 landcover map representing the future (2021–2050). This time, effects of climatic change on hydrology were evaluated using the 2019 landcover data as opposed to the 1984 landcover (Appendix 5-1).

5.4 Results and discussion

5.4.1 Sensitivity analysis

Sensitivity analysis of the full set of the parameters used during calibration was done using the student t-test, with its significance assessed using the *p*-value based on 500 simulations. A parameter is more sensitive if it has a relatively larger absolute t-value accompanied by a relatively lower *p*-value (< 0.05) (Abbaspour, 2015). The most sensitive parameters for streamflow and ET for calibration of streamflow were SOLWAC, CN2.mgt, CH_K2 and groundwater delay (GW_DELAY) among others (Table 5-4). These parameters were also sensitive for sediment load. Additionally, sediment load, was more sensitive to USLE_P, CH_N2 and PRF_BSN. The full names of these parameters are given in Table 5-4.

Table 5-4: Sensitivity of parameters for streamflow and sediment load

Parameter name	t-Statistic	p-value	Parameter description
R__SOL_AWC().sol	-36.4139	0.0000	Available water capacity of the soil layer
R__CN2.mgt	15.9777	0.0000	SCS runoff curve number
V__CH_K2.rte	-9.9076	0.0000	Effective hydraulic conductivity in main channel alluvium
V__GW_DELAY.gw	7.5407	0.0000	Groundwater delay
V__GW_REVAP.gw	-2.8210	0.0050	Groundwater “revap” coefficient. “revap” is evaporation from shallow aquifer.
R__SOL_BD().sol	2.7910	0.0055	Moist bulk density
V__GWQMN.gw	-2.5690	0.0105	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)
V__REVAPMN.gw	2.1167	0.0348	Threshold depth of water in the shallow aquifer for “revap” to occur (mm)
V__USLE_P.mgt	-1.5432	0.1245	Universal Soil Loss Equation (USLE) equation support practice factor
V__PRF_BSN.bsn	0.6777	0.4988	Peak rate adjustment factor for sediment routing in the main channel
V__RCHRG_DP.gw	-0.6413	0.5216	Deep aquifer percolation fraction
V___CH_N2.rte	-0.4691	0.6395	Manning's "n" value for the main channel

V __ means the existing (or default) parameter value was replaced by a given value,

R__ means an existing (default) parameter value was multiplied by (1+ a given value)

5.4.2 Hydrological model performance

With the calibration considerations outlined in section 5.3.3, the model evaluation criteria proposed by Moriasi et al. (2007) for NSE and Abbaspour (2022) for the *p-factor* and *r-factor* indicated satisfactory model performance (Table 5-5). This is despite the difficulties in calibrating the catchment due to weirs on the main channel. The model could thus be used for simulating the potential future impacts and evaluating the performance of NbS.

Table 5-5: Calibration and validation metrics

	Period	P-factor	R-factor	Nash Sutcliffe Efficiency	Kling Gupta Efficiency	PBIAS
Calibration						
Streamflow	1975 - 1979	0.75	1.10	0.70	0.78	5.90
Evapotranspiration	2000 - 2005	0.36	0.16	0.64	0.76	-1.90
Sediment load	1997 - 1998	0.61	1.01	0.49	0.50	-43.5
Validation						
Streamflow	1980 - 1982	0.71	1.11	0.71	0.83	-10.3
Evapotranspiration	2006 - 2010	0.32	0.13	0.71	0.76	1.60
Sediment load	1999 - 2000	0.28	0.12	0.18	0.40	31.7

The column indicating fitted value in Table 5-3 was only to show the values upon which the objection function of NSE, PBIAS, and KGE indicated in Table 5-5 is based. These were not written to the model. Instead, the final calibration ranges are the calibrated model used for scenario analysis. The calibration results are shown graphically in Figure 5-2. Generally, many of the peaks and the low flows were within the prediction range of the model as defined by the 95PPU for streamflow (Figure 5-2). For ET, the peaks were slightly under predicted, but generally well simulated and the PBIAS was very good (Table 5-5). Although sediment load was poorly calibrated, the model was still indicative of the sediment dynamics in the catchment, and thus still usable for scenario analysis.

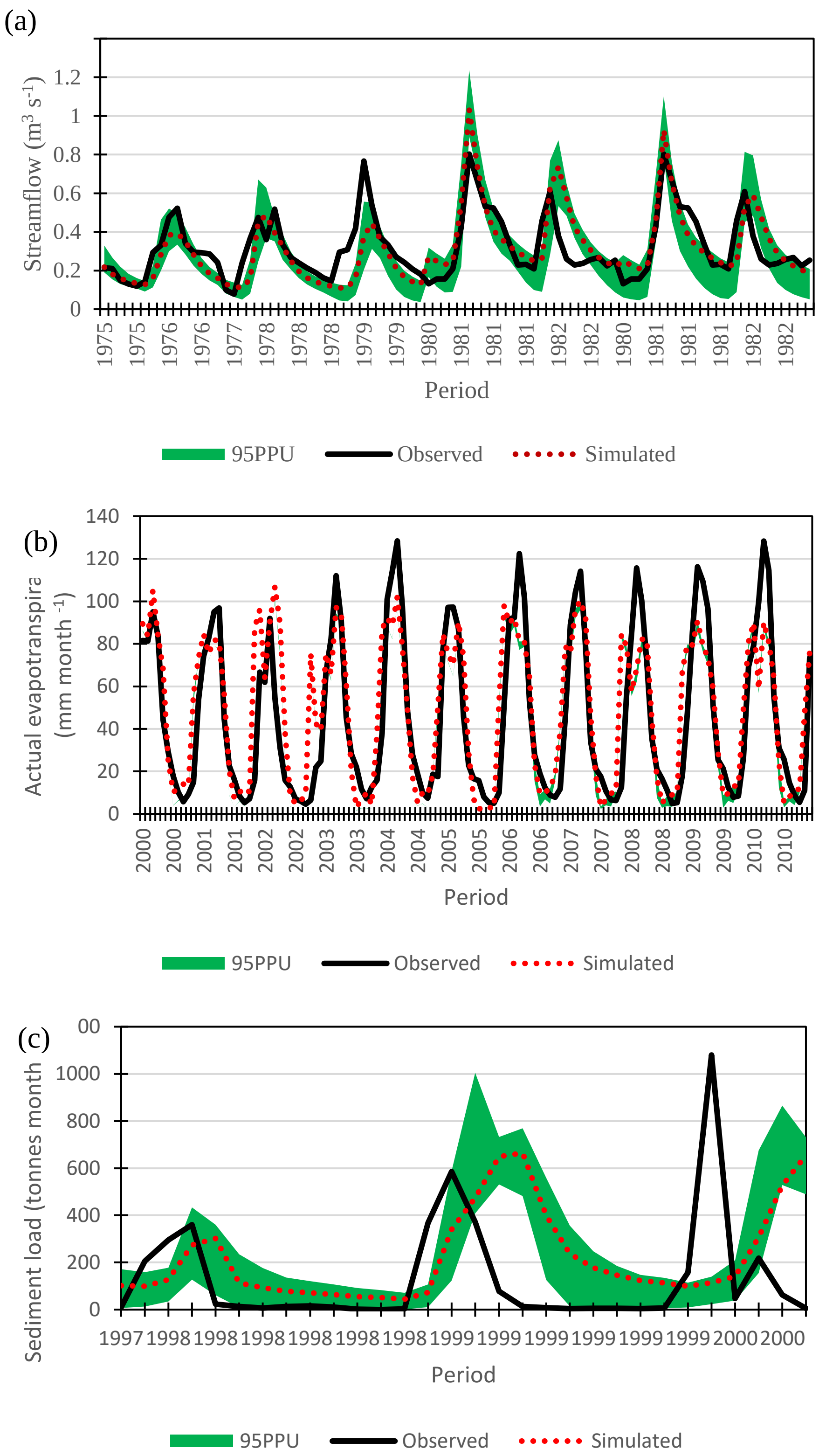


Figure 5-2: Observed versus simulated data for (a) streamflow, (b) evapotranspiration and (c) sediment load

5.4.3 Projected changes in climatic and weather extremes by 2050

5.4.3.1 The MIROC5 model

The MIROC5 model projected a 1% decrease in total rainfall under the RCP 4.5 scenario as indicated by the annual total rainfall (PRCPTOT) and a 7% decrease in the number of days with heavy rain (R10MM) compared to be historical period (Table 5-6). However, under the RCP 8.5 scenario, a 6% increase in total rainfall was projected. The one-day maximum rainfall (RX1DAY) was projected to increase by about 16% and 19% for both the RCP 4.5 and RCP 8.5 scenarios (Table 5-6), pointing to increased rainfall intensities. The wet spell length (consecutive wet days – CWD) was projected to decrease (by 23% and 15% under the RCP 4.5 and RCP 8.5 scenarios respectively) compared to the baseline. The mean temperature (TMM) would increase by about 2˚C for both the RCP 8.5 and RCP 4.5 scenarios.

Table 5-6: Changes in annual climatic indices

	PRCPTOT %	RX1DAY %	R10MM %	CDD %	CWD %	TMM ˚C	TXX ˚C
MIROC5_RCP45	-1.07	15.83	-7.03	-0.20	-23.17	1.68	0.97
MIROC5_RCP85	6.06	18.58	0.17	10.03	-14.78	1.94	1.27
MPI-ESM-LR_RCP45	11.72	7.08	5.23	2.40	5.98	1.46	1.11
MPI-ESM-LR_RCP85	11.90	11.58	3.92	9.08	-6.21	1.73	1.28
Ensemble mean RCP45*	5.90	3.16	16.40	1.50	-7.86	1.49	0.86
Ensemble mean_RCP85*	11.72	20.43	30.52	-1.39	-1.64	1.78	0.99

* Ensemble of five GCMs from table 5-1. PRCPTOT - Total rainfall, RX1DAY - one-day rainfall intensity, R10MM - number of days with heavy rains (rainfall ≥ 10 mm), CDD - consecutive dry days, CWD - consecutive wet days, TMM - mean daily temperature and TXX - maximum value of daily maximum temperature (hottest day in the year)

5.4.2.2 The MPI-ESM-LR model and the ensemble mean

The MPI-ESM-LR model and the ensemble climate projected an increase in annual rainfall for the future period (Table 5-6). The MPI-ESM-LR projected an increase in annual rainfall by about 12% (Table 5-6), representing an increase in annual rainfall of about 82 mm and 83 mm under the RCP 4.5 and RCP 8.5 climate respectively. The ensemble mean dataset also projected a 12% (81 mm) increase in rainfall under the RCP 8.5 and a 6% (41 mm) increase under the RCP 4.5 scenario.

Increases in rainfall were generally accompanied by adverse changes in other weather extremes (Table 5-6). For example, under the ensemble, there was a projected increase in rainfall intensities (RX1DAY) by 3% (RCP 4.5) and 20% (RCP 8.5). The dry spell (CDD) length was also projected to increase by 1.5% for the RCP 4.5 scenario although it was projected to decrease under the RCP 8.5 scenario by 1.4%. The wet spell (CWD) length was projected to decrease by 8% under the RCP 4.5 and about 2% under the RCP 8.5 scenario of the ensemble. Daily mean air temperature (TMM) was projected to increase by 1^{o}C and about 2^{o}C under the RCP 4.5 and RCP 8.5 scenarios respectively. Daily maximum air temperature (TXX) was also projected to increase by about 1^{o}C under the ensemble for both RCP 4.5 and RCP 8.5 scenarios (Table 5-6).

These results are consistent with Chisola et al. (2020) and Chapter three which observed increasing dry spell length and rainfall intensities based on historical observed data and found these to be among the main climatic stressors on water availability in the Kaleya River Catchment as opposed to the annual rainfall totals. The findings also collaborate with the projected increase in CCD and RX1DAY for the southern region of Zambia (GRZ, 2020).

Similar increasing trends in dry spells have also been reported in other drier parts of Southern Africa such as southern Zimbabwe (Sibanda et al., 2018).

In general, all the models projected an increase in air temperature by 1 - 2˚C for both RCP 4.5 and RCP 8.5 scenarios by 2050 as indicated by the annual mean daily air temperature (TMM) and the annual maximum value of daily maximum air temperature (TXX) (Table 5-6). The increase in daily mean air temperature is within the 2 - 5˚C projected increase by 2100 for southern Africa (Kusangaya et al., 2014). Both the annual rainfall totals and air temperatures tended to be higher under the RCP 8.5 scenario compared to the RCP 4.5 scenario for all the GCMs (Table 5-6). Similar results have been projected for the southern parts of Zambia (GRZ, 2020).

5.4.4 Changes in blue water flow (streamflow) and sediment load under projected climate change scenarios by 2050

5.4.4.1 Blue water (streamflow) and sediment load changes under the MIROC5 model

The predicted impacts of various GCMs under the various hydrological model prediction uncertainty levels are given in Tables 5-7 and 5-8 for streamflow and sediment load respectively. Here, only the values at the 50% uncertainty level, also called the median (M95PPU) are discussed. Under the RCP 4.5 scenario, the MICROC5 climate data predicted a 3% reduction in rainy season flows (Table 5-7), and a 2% (544 m^3 day^{-1}) decrease in total streamflow at the annual scale (Table 5-7 and Appendix 5-2), accompanied by a 7% (320 tonnes $year^{-1}$) decrease in sediment load (Table 5-8 and Appendix 5-3). These could be explained by the projected decrease of 1% and 7% in total rainfall and number of days with heavy rainy (R10MM) respectively (Table 5-6).

For RCP 8.5 scenario, annual streamflow was predicted to increase by 20% (5,668 m^3 day $^{-1}$) following a 6% increase in projected rainfall. However, this was accompanied by a 7% (424 tonnes year $^{-1}$) increase in sediment load, which could be linked to the 19% increase in one day rainfall intensity (RX1DAY). Just like under the RCP 4.5, the major changes to the predicted median streamflow and sediment load under the RCP 8.5 were in the rainy season (Table 5-7 and Table 5-8).

Table 5-7: Projected climate change impacts on blue water flow (streamflow)

		MICROC 5				MPI_ESM_LR				Ensemble			
	Uncertainty level (%)	RCP 4.5	RCP 4.5	RCP 8.5	RCP 8.5	RCP 4.5	RCP 4.5	RCP 8.5	RCP 8.5	RCP 4.5	RCP 4.5	RCP 8.5	RCP 8.5
		m^3 day $^{-1}$	%	m^3 day ^{1}	%	m^3 day $^{-1}$	%	m^3 day $^{-1}$	%	m^3 day $^{-1}$	%	m^3 day $^{-1}$	%
Dry season	2.5 (L95PPU)	109	1	844	8	3204	34	3404	26	2218	17	4460	26
	97.5 (U95PPU)	86	0	85	0	5057	29	5451	24	3087	16	6078	23
	50 (M95PPU)	-32	0	823	5	4161	31	4408	25	2602	16	5311	24
Rainy season	2.5 (L95PPU)	-992	-3	4611	14	14629	51	14836	34	5725	29	12338	38
	97.5 (U95PPU)	-1388	-3	6423	12	17874	40	18129	29	7542	23	16270	33
	50 (M95PPU)	-1119	-3	5456	13	16118	45	16486	32	6443	25	14039	35
Annual average	2.5 (L95PPU)	-442	-2	4905	22	8916	47	9120	32	3971	24	8399	34
	97.5 (U95PPU)	-618	-2	6332	17	11466	37	11790	27	5314	20	11174	30
	50 (M95PPU)	-544	-2	5668	20	10139	42	10447	30	4523	21	9675	31

RCP – Representative Concentration Pathway

5.4.3.2 Streamflow and sediment load changes under the MPI-ESM-LR model

Taking the median (50% uncertainty level), the *MPI-ESM-LR* climate model predicted a 42% increase in annual streamflow under the RCP 4.5 and a 30% increase under the RCP 8.5 scenario (Table 5-7). These changes represent an increase in annual streamflow by about 10,139 m^3 day^{-1} under the RCP 4.5 and 10,447 m^3 day^{-1} under the RCP 8.5 scenarios.

However, it can be observed that the RCP 8.5 scenario had higher predicted streamflow in terms of magnitudes (in m^3 day^{-1}) (Appendix 5-2) because of the rainfall intensities (RX1DAY) that increased by 12% compared to the 7% increase under RCP 4.5 scenario as shown in Table 5-6. Consequently, sediment load was also predicted to increase slightly higher under RCP 8.5 scenario (92% or 2,010 tonnes $year^{-1}$) than under the RCP 4.5 scenario (86% or 1,934 tonnes $year^{-1}$) (Appendix 5-3). Although dry season streamflow was predicted to increase, the increases in volumes terms were smaller compared to the increases in rainy season streamflow (Table 5-7).

Table 5-8: Projected climate change impacts on sediment load

		MICROC 5				MPI_ESM_LR				Ensemble			
	Uncertainty level (%)	RCP 4.5 tons $year^{-1}$	RCP 4.5 %	RCP 8.5 tons $year^{-1}$	RCP 8.5 %	RCP 4.5 tons $year^{-1}$	RCP 4.5 %	RCP 8.5 tons $year^{-1}$	RCP 8.5 %	RCP 4.5 tons $year^{-1}$	RCP 4.5 %	RCP 8.5 tons $year^{-1}$	RCP 8.5 %
Dry season	2.5 (L95PPU)	47	11	-184	-45	187	64	216	74	33	37	89	100
	97.5 (U95PPU)	-20	-1	-239	-13	536	40	599	44	282	19	654	45
	50 (M95PPU)	13	1	-59	-5	392	43	431	47	271	33	601	73
Rainy season	2.5 (L95PPU)	-292	-12	435	18	1353	68	1296	65	232	40	580	100
	97.5 (U95PPU)	-448	-8	584	11	1683	36	1772	38	793	24	1715	52
	50 (M95PPU)	-332	-8	482	12	1542	44	1579	45	723	33	1574	71
Annual total	2.5 (L95PPU)	-245	-1	251	-27	1540	132	1512	139	265	77	668	200
	97.5 (U95PPU)	-468	-10	345	-2	2219	75	2371	82	1075	43	2370	97
	50 (M95PPU)	-320	-7	424	7	1934	86	2010	92	994	65	2175	144

RCP – Representative Concentration Pathway

5.4.3.3 Streamflow and sediment load changes under the ensemble mean dataset

Taking the median (50% uncertainty level), the ensemble mean dataset predicted a 31% (9,675 m^3 day^{-1}) increase in annual streamflow under RCP 8.5, accompanied by a sediment load increase of 144% (2,175 tonnes $year^{-1}$) (Table 5-8, Appendix 5-2 and Appendix 5-3). These predictions are expected given the 12% increase in annual rainfall, a 20% increase in rainfall intensity (RX1DAY), and a 31% increase in days with heavy rains (R10MM). For the RCP 4.5 scenario, streamflow was predicted to increase by 21% (4,523 m^3 day^{-1}), while sediment load was predicted to increase by 65% (994 tonnes $year^{-1}$) as shown in Table 5-8 and Appendix 5-3. These changes could be attributed to the projected 6% increase in total rainfall, a 3% increase in rainfall intensity (RX1DAY), and a 16% increase in the number of days with heavy rain (R10MM) under the RCP 4.5 scenario (Table 5-6). With respect to changes at seasonal scale, the predicted increases in dry season streamflow volumes were minor are they were about 2 - 3 times less than the increases in the rainy season (Table 5-7).

5.4.5 Changes in green water flow (evapotranspiration) under projected climate change scenarios by 2050

The *MICROC5* model under the RCP 4.5 scenario predicted no change in ET at the annual timescale. This is because the predicted increase in ET in the rainy season was the same as the decrease in dry season ET, hence they compensated for each other at the annual scale (median results in Table 5-9 and Appendix 5-4). However, under the RCP 8.5 scenario, the predicted increases in rainy season ET were less than the decreases in dry season ET, hence a 7% (34 mm) reduction in ET was predicted at the annual scale. This was unexpected given the 2% increase in temperature predicted under this scenario (Table 5-6).

On the other hand, the *MPI-ESM-LR* model as expected, predicted a 2% (10 mm) and 1% (5 mm) increase in annual ET (50% probability values) (Appendix 5-4). As opposed to the MICROC5 model, here the dry season was featured with higher ET increases compared to the rainy season (Table 5-9). These predictions can be explained by the 1 - 2% increase in mean air temperature under this model (Table 5-6).

The ensemble mean dataset also predicted a 2% (9 mm) increase in ET under the RCP 4.5 scenario at the annual scale, but no change under the RCP 8.5 scenario (Table 5-9). Here, the changes in ET in the dry and rainy season was almost balanced. About 2% increase in air temperature was projected under this scenario (Table 5-6), so the results fall within what could generally be expected.

Table 5-9: Projected climate change impacts on green water flow (Evapotranspiration)

		MICROC 5				MPI_ESM_LR				Ensemble			
	Uncertainty level (%)	RCP 4.5	RCP 4.5	RCP 8.5	RCP 8.5	RCP 4.5	RCP 4.5	RCP 8.5	RCP 8.5	RCP 4.5	RCP 4.5	RCP 8.5	RCP 8.5
		mm	%	mm	%	mm	%	mm	%	mm	%	mm	%
Dry season	2.5 (L95PPU)	-4	-2	-57	-31	6	3	3	2	2	1	1	0
	97.5 (U95PPU)	-2	-1	-59	-30	10	5	5	2	6	3	2	1
	50 (M95PPU)	-3	-1	-58	-30	9	4	5	2	4	2	2	1
Rainy season	2.5 (L95PPU)	0	0	22	8	-3	-1	-5	-2	2	1	-4	-1
	97.5 (U95PPU)	3	1	25	8	3	1	3	1	6	2	3	1
	50 (M95PPU)	2	1	24	8	1	0	0	0	5	1	0	0
Annual total	2.5 (L95PPU)	-4	-1	-35	-8	4	1	-1	0	4	1	-3	-1
	97.5 (U95PPU)	1	0	-34	-7	14	2	9	2	12	2	5	1
	50 (M95PPU)	0	0	-34	-7	10	2	5	1	9	2	2	0

RCP – Representative Concentration Pathway

5.4.6 Effects of landcover and climate change on sediment load, and green and blue water

Climate change predicted the larger individual effects on sediment load and blue water (streamflow), while landcover change had the larger individual effect on green water storage (soil moisture) (Table 5-10). The magnitude of the landcover effects were almost the same regardless of the climate change scenario (Table 5-10). Climate change predicted higher streamflow increase of 31% (RCP 8.5) and 21% (RCP 4.5) while landcover change predicted increase in streamflow of 12% under both RCP 4.5 and RCP 8.5 scenarios. However, the combined landcover and climate change amplified each other's effect, leading to streamflow increase of 41% under the RCP 8.5 scenario and 30% under the RCP 4.5 scenario.

Table 5-10: Individual and combined effects of landcover and climate change at annual scale

	Water balance	Water type	Landcover change	Climate change	Landcover & climate change
			% Change	% Change	% Change
RCP 4.5	Streamflow	Blue water	12	21	30
	Soil moisture	Green water storage	-20	7	-12
	Evapotranspiration	Green water flow	-3	2	-1
	Sediment load	-	10	65	87
RCP 8.5	Streamflow	Blue water	12	31	41
	Soil moisture	Green water storage	-21	5	-13
	Evapotranspiration	Green water flow	-2	0	-2
	Sediment load	-	10	144	158

The lower streamflow increases predicted by the landcover change scenario were due to changes in streamflow occurring in opposite directions for the rainy and dry seasons, thereby cancelling each other at the annual scale. Figure 5-3 presents the streamflow results at the season scale. It shows that while climate change increased both dry and rainy season flows, landcover change only increased the rainy season flows, and ended up reducing the dry season flows (Figure 5-3). Therefore, the combined landcover and climate change reversed some of the gains in dry season flows that were predicted under the RCP 4.5 and RCP 8.5 climate scenarios respectively and amplified the rainy season flows (Figure 5-3).

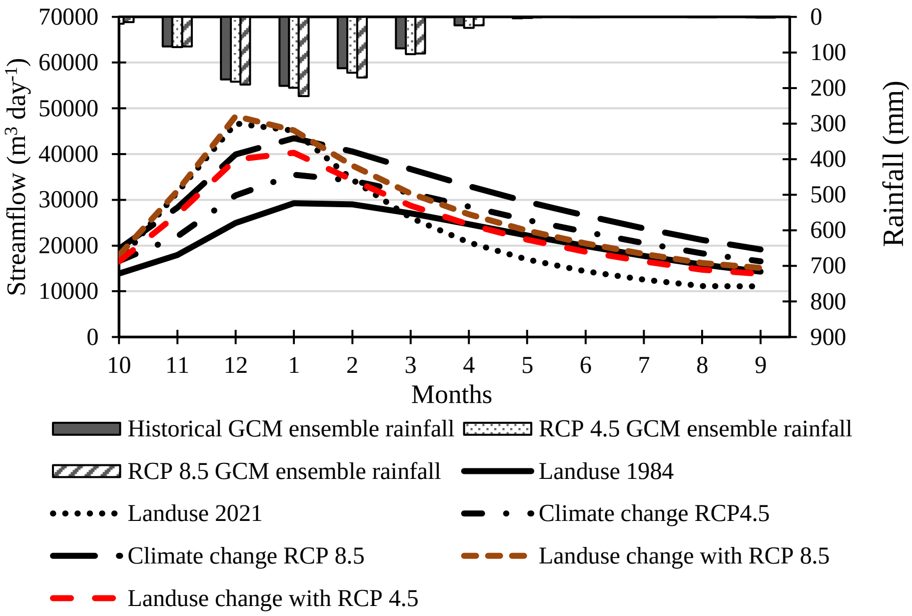


Figure 5-3: Average seasonal changes in streamflow and rainfall

With respect to green water, landcover change predicted reduced green water storage (soil moisture) by 20% under the RCP 4.5 scenario and 21% under the RCP 8.5 scenario. Climate change on the other hand predicted slight increases in green water storage (Table 5-10). However, the combined landcover and climate effects were predicted to lead to a reduction in green water storage by about 12% and 13% under the RCP 4.5 and RCP 8.5 scenarios respectively. For green water flow (ET), the landcover change scenario was associated with minor reductions possibly due to less vegetation cover (Appendix 5-1), while climate change was associated with increases in ET, although the changes for both cases were minimal.

Landcover change alone predicted increased sediment load by about 10% for both RCP 4.5 and RCP 8.5 scenarios. Climate change alone predicted increased sediment load by 65% (RCP 4.5) and 144% (RCP 8.5). However, landcover change and climate change amplified each other's effect, leading to a predicted 87% increase in sediment load under the RCP 4.5 scenario and 158% increase under the RCP 8.5 scenario (Table 5-10).

5.4.7 Implications for catchment management under a changing environment

Although some studies have predicted a rainfall decrease of up to 23% in southern Africa (Conway et al., 2015, Banze et al., 2018), the 6 - 12% predicted increase in rainfall in this study (for the ensemble) is consistent with the observed increasing rainfall trends in the region based on both observed (Chapter three) and projected data from other GCMs in southern Zambia (Chisola et al., 2020, GRZ, 2020). The predicted increase in annual rainfall was generally associated with increased rainfall intensity (RX1DAY), increased dry spell length (CDD) and a decreased duration of wet spells (CWD). These changes were predicted to contribute to relatively higher percentage increases in blue water flow (streamflow), and even higher percentage increases in sediment load.

There is, therefore, a need to take advantage of the likely increase in rainfall, rainfall intensity and runoff through interventions that will take this rainwater as a key resource. Such interventions could be aimed at keeping stormwater within the catchments longer for use during dry spells and dry periods. Interventions could include well-planned reservoirs with environmental flow release capabilities as proposed in Chapter three and by Chisola et al. (2022).

While the climate change effects implied increased blue water by 2050 mainly due to higher rainfall amounts and intensities, the landscape changes could reduce the infiltration of this water and result in reduced dry season flows. The increased rainy season streamflow implies increased chances of flush floods, even in the rural landscapes that typically have not been experiencing flush floods. The flush floods witnessed in January 2022 in southern Zambia (https://floodlist.com/africa/zambia-floods-southern-province-january-2022, accessed 09/10/2022) where the study area falls could become a common occurrence if the landscape change patterns discussed in Chapter three continue.

The reduced green water storage is likely to be mainly driven by landscape changes interacting with climatic and weather extremes as indicated by Chapter three. This could therefore threaten food production and ecosystem productivity needed for increased community resilience to climate change. Generally, communities in southern Zambia have the tendency to put their crop fields in low lying areas near valleys and stream channels as an adaptation measure to reduced soil moisture during dry spells. But these are the areas that are likely to experience flush floods given the predicted increases in rainfall intensities and rainy season flows. This could therefore result in crop damage incidences such as the ones reported in the 2021/2022 season in flush flood affected areas, where it was reported that over 8,000 ha of crop fields had been submerged (IFRC, 2022).

Additionally, the higher increase in sediment load under the combined landcover and climate change would exacerbate the siltation problem in river catchments and potentially reverse any gains on streamflow, as siltation could reduce storage capacities. The average siltation rate of 30 mm year $^{-1}$ between 1973 and 1986 reported by Walling et al. (2001) in small reservoirs (dam wall height $\leq$ 10 m) in the study catchment could now be higher due to the landcover changes that have taken place since then. Hence there is need for interventions to reduce sediment load, increase green water storage that is important for food and terrestrial ecosystems, and maintain or increase groundwater which is the main source of water in meso-scale catchments.

In this regard, soil and water conservation-oriented Nature based Solutions (NbS) such as conservation tillage with residue management, reforestation of larger forest patches as recommended in Chapter three and recharge structures such as check dams and infiltration pits could be used. These were outside the scope of this chapter but are a subject of investigation in chapter six.

Lastly, although dry season flows were predicted to increase except under the MICROC5 RCP 4.5 scenario, the actual increases in terms of volumes are smaller. This means they may not be able to keep pace with increasing irrigation water demands that are likely to ensue because of the increasing dry spell length. The need to grow more food to feed the growing population will also add to the pressure. Already chapter three has demonstrated that irrigation expansion is among the major drivers of reduced blue water (streamflow) in the dry season in the case study catchment. A further assessment of these interactions between irrigation expansion and dry season water availability in the context of the future climate could be explored in future research.

5.5. Conclusions

The study found that annual rainfall and temperature are projected to increase by 2050 over the Kaleya River Catchment. These could be accompanied by adverse changes in extreme events, in form of rainfall intensity and longer dry spell length. Generally, these changes could lead to increased streamflow, ET, and sediment load. While climate change could increase water availability in both the rainy and dry seasons, landcover change could reverse any potential water gains in the dry season. The study recommends interventions to harvest this rainfall and rainy season runoff, to keep the water longer in the catchment, where it could be needed to meet the water demands that could equally rise due to longer dry spells.

In summary, chapter five (Figure 5-4) provided an outlook of the future climate in the case study catchment. The implications of the future changes in climate and extreme weather events on water availability and sediment load were examined. The hydrological modelling was confined to the upper Kaleya River Catchment due to the problems in calibrating the model in the middle catchment which would have introduced more uncertainties due to dams (chapters three and four). The results in chapter five can still be extrapolated to the entire catchment and similar catchments elsewhere. However, examining the future changes would be incomplete without assessing the effectiveness of nature-based solutions recommended from chapter three to five. Chapter six was therefore dedicated to fill this gap.

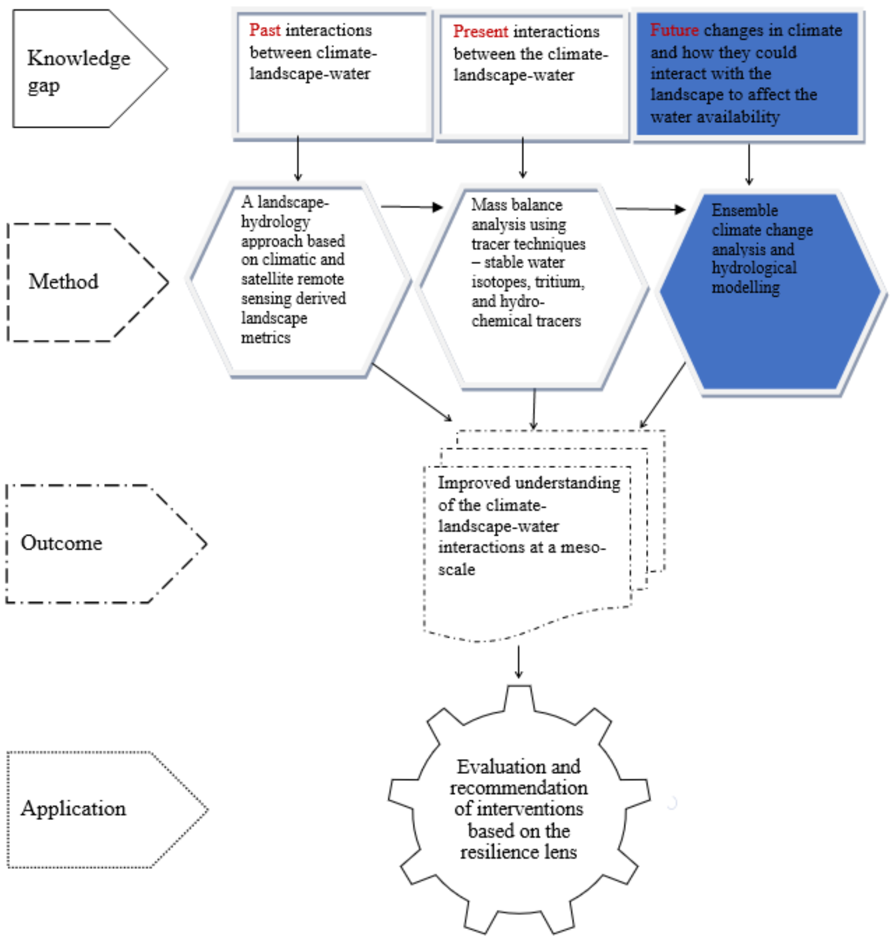


Figure 5-4: Analytical framework showing the focus for chapter five

Chapter 6

Efficiency of Nature-based Solutions for water resource and sediment load management under the future climate changes: a green and blue water perspective

Abstract

This study evaluated the efficiency of Nature-based Solutions (NbSs) for managing water availability and sediment load under different climate change scenarios in the case study Kaleya River Catchment, Zambia. An ensemble of five downscaled Global Climate Models was used based on the Representative Concentration Pathways (RCPs), RCP 8.5 and RCP 4.5 scenarios. The NbSs virtual experiments were conducted using the Soil and Water Assessment Tool model. The results showed that the reforestation NbS predicted the largest reductions in surface blue water (surface runoff) by 74% under the historical, 69% under the RCP 4.5 and 62% under the RCP 8.5 climate scenarios. Reforestation also predicted increased deep aquifer recharge by 39% (historical), 26% (RCP 8.5) and 23% (RCP 4.5 scenario). Baseflow contribution to streamflow under reforestation was predicted to increase by 11% (historical) and 2% (RCP 8.5) but not under RCP 4.5 scenario (-2%), while green water flows (evapotranspiration) would increase by 2% (historical), and 3% (both RCP 4.5 and RCP 8.5%). Recharge structures predicted reduced surface runoff by 2 to 4 %, increased baseflow contribution and deep aquifer recharge by about 4%, and no change in ET under all climate scenarios. Conservation tillage had a negligible effect on water balance components. On sediment load, the highest reduction was predicted under recharge structures (34% historical, 24% RCP 4.5 and 15% RCP 8.5 scenario), followed by reforestation (15% historical, 7% RCP 4.5 scenario and 6% RCP 8.5 scenario), and finally conservation tillage (4% historical, 2% RCP 4.5 and 1% RCP 8.5 scenario). The best results for both water and soil conservation were under the combination of all NbS scenario. From the green-blue water perspective, the study concluded that these nature-based solutions have the potential to manage the increased rainfall and its intensities, by reducing the eventual high rainy season surface runoff and storing it in the catchment for much longer periods as deep groundwater and baseflow and increasing the productive green water flows and reducing sediment loads.

Keywords: groundwater; green water flow; sediment load; reforestation; weather extremes

6.1 Introduction

Interactions among changing landscape patterns and climate continue to alter the partitioning of precipitation into green and blue water (Hoff, 2009, Olsson et al., 2016, Rockström et al., 2014). Green water is the water that enters the soil and is later lost as water vapour through evapotranspiration (Rockström and Falkenmark, 2000, Falkenmark and Rockström, 2006). It also includes interception loss. The transpiration component constitutes the productive part of green water useful for plant growth, and productivity (Falkenmark and Rockström, 2010). Blue water is water in rivers, reservoirs, and aquifers (Hoekstra, 2002, Falkenmark and Rockström, 2010, Hoekstra et al., 2011).

The conventional water management paradigm and engineering tradition are centred on management of streamflow as the primary water resource (Hoekstra et al., 2011, Keys and Falkenmark, 2018). However, there is a need to recognise how different types of water contribute to the resilience of rural communities who mainly occupy meso-scale semi-arid catchments (where precipitation is less than potential evapotranspiration). Firstly, in such environments, green water flows (transpiration component) are often at the core of livelihood activities, supporting not only food and fibre production, but also grazing for livestock, which in turn provides additional household incomes necessary for resilience against environmental shocks (Schyns et al., 2019). As such, productivity is limited by the shortage of green water in time and space (Keys and Falkenmark, 2018, Schyns et al., 2019). Secondly, it is the groundwater and reservoirs component of blue water upon which communities are often more dependent than streamflow since many streams are ephemeral by nature (Jonathan Davies et al., 2016, Gaye and Tindimugaya, 2019, Cecchi et al., 2020). Thirdly, the reservoirs that are expected to buffer the communities in periods of extended dry spells are becoming less effective due to loss in storage capacities arising from siltation (Walling et al., 2001, Sichingabula et al., 2015, Cecchi et al., 2020, Sichingabula et al., 2020).

The green-blue water approach (Falkenmark et al., 2004, Falkenmark and Rockström, 2006, Falkenmark et al., 2014, Rockström et al., 2014) is thus relevant for water resource management under a changing environment (changing environment refers to both climate and landscape change in this study) in semi-arid areas. The approach recognises precipitation as the primary resource for management, whereby the landscape can be manipulated to influence how precipitation is partitioned into green and blue water (Falkenmark et al., 2004, Falkenmark and Rockström, 2006, Hoff, 2009, Rockström et al., 2014). Along with the green-blue water approach (Falkenmark et al. 2004, Falkenmark and Rockström 2006, Falkenmark and Rockström 2010), is the water footprint assessment concept (Hoekstra 2002, Hoekstra et al. 2011) that has developed almost in parallel, but more as an assessment framework for evaluating water value chains and the sustainability of water use among others (Le Roux et al., 2017, Van der Laan et al., 2021).

The green-blue water approach advocates for the inclusion of land in the integrated water resources management (IWRM) concept to ensure that the landscape and division of precipitation into green and blue water, and the trade-offs thereof are at the core of management decisions (Falkenmark and Rockström 2006, Falkenmark and Rockström 2010). Hence, it advocates for integrated land and water resources management (ILWRM) (Falkenmark and Rockström 2006, Rockström et al. 2014).

Solutions to adapt to the changing climate in this regard could lie in interventions such as Nature-based Solutions (NbSs) (Lafortezza et al., 2018, Martín et al., 2020). The International Union for Conservation of Nature (IUCN) defines Nature-based Solutions (NbSs) as human interventions aimed at protecting, managing, and restoring ecosystems to generate benefits for both society and the environment, thereby increasing resilience (Cohen-Shacham et al., 2016). The NbSs have become especially popular in water resource management discourse due to the likely landscape scale benefits on soil and water conservation and their potential to increase resilience by creating socio-economic and ecological co-benefits (Raymond et al., 2017, Martín et al., 2020, Brauman et al., 2022).

Thus, the current drive towards NbSs to deal with water challenges sits well with the concept of the green-blue water approach (or ILWRM framework). While in the current framing, the NbS concept seems to be primarily focussed on achieving streamflow goals, it is a rain-based management concept to a large extent. And therefore, a green water and blue water perspective becomes important in evaluating the performance of NbSs.

For the Kaleya River Catchment in southern Zambia, the findings in chapter three and five have identified increased rainfall intensities, longer dry spells and increased sediment load among the major factors that could affect future water availability, and thus call for management interventions. Other studies in the catchment have also pointed out the threat posed by sediment load and siltation of reservoirs with respect to water storage (Sichingabula et al., 2000a, Collins et al., 2001, Chisola et al., 2020, Sichingabula et al., 2020). As such, some NbSs have been suggested in the catchment in the past (Collins et al., 2001, Chisola et al., 2020, Sichingabula et al., 2020) and in this thesis (Chapters three to five). However, the effectiveness of these measures under changing climatic regimes has not been quantified.

Assessments are needed on how the future changes in climate, including extremes, could affect the effectiveness of NbSs in achieving more resilient water resources management in order to support decision making (Calliari et al., 2019). This study hypothesised that NbSs interventions could be used to manage the negative effects of future climate and weather extremes as they could reduce the increased surface runoff generation and sediment load and increase local green and blue water storage. This hypothesis was tested through the lenses of the green-blue water perspective in the upper Kaleya River Catchment (Figure 6-1) as a case study.

6.2 The study area

The upper Kaleya River Catchment was chosen for this case study to reduce hydrological model uncertainties in the NbS assessments. These challenges were briefly discussed in Chapter three (Chisola et al., 2020), Chapter four (Chisola et al., 2022) and Chapter five. The results could still be extrapolated to the whole catchment and other similar semi-arid meso-scale catchments.

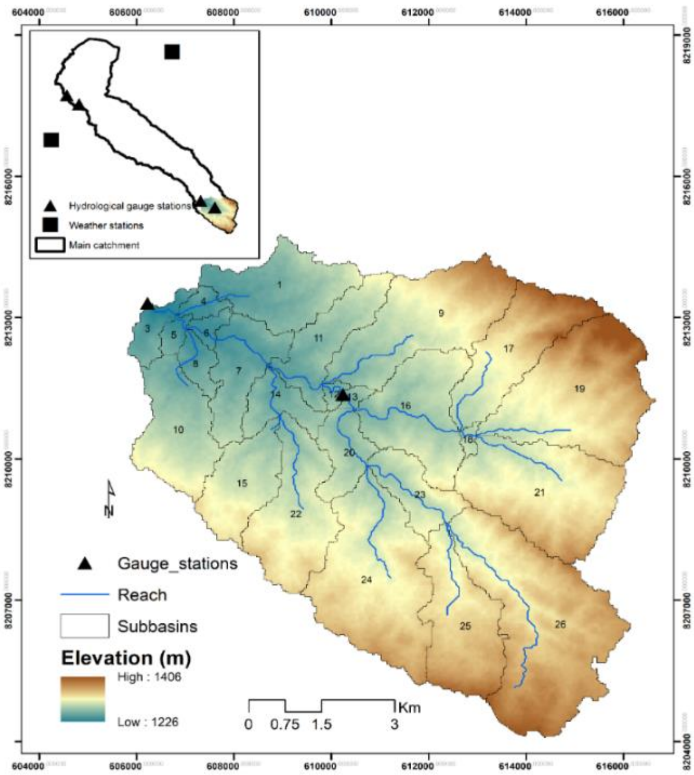


Figure 6-1: Upper Kaleya River Catchment

6.3 Materials and methods

6.3.1 Data

The ensemble GCM climate data discussed in Chapter five were used based on the historical (1975 - 2005), and future climate (2021 - 2050). The historical GCM data were only available up to 2005, hence the restriction of the baseline period to 1975 - 2005. Although observed weather data could have been used for the historical (baseline) period, the idea was to hold the GCM uncertainties constant by using only GCM data for both the baseline and the future periods. This could help to better assess how various NbS interventions would affect water availability and sediment load under climate change. The SWAT model (Chapter five) was initialised using the 2019 landcover map generated as described in Chapter three. This landcover data was linked to the SWAT in-built database using a look up table as explained in Chapter five.

6.3.2 Data analysis

The SWAT hydrological model developed and calibrated in Chapter five was used stochastically (through the calibrated parameter ranges) to evaluate the effectiveness of NbS interventions proposed in Chapter five in managing rainfall extremes for increased blue and green water storage and reducing sediment load under various climate change scenarios. The SWAT model can simulate various green and blue water components as illustrated in Figure 6-2, where:

$$\begin{aligned} Blue\ water\ &=\ Surface\ runoff\ (SURQ)\ +\ Lateral\ flow\ (LATQ) \\ &+\ Return\ flow\ (GW\_Q) \\ &+\ Recharge\ to\ deep\ aquifer\ (DA\_RCHG) \end{aligned} \qquad (6-1)$$

$$Green\ water\ storage\ =\ Initial\ soil\ moisture\ (SW_{INIT}) \qquad (6-2)$$

$$Green\ water\ flow\ =\ Actual\ evapotranspiration\ (ET) \qquad (6-3)$$

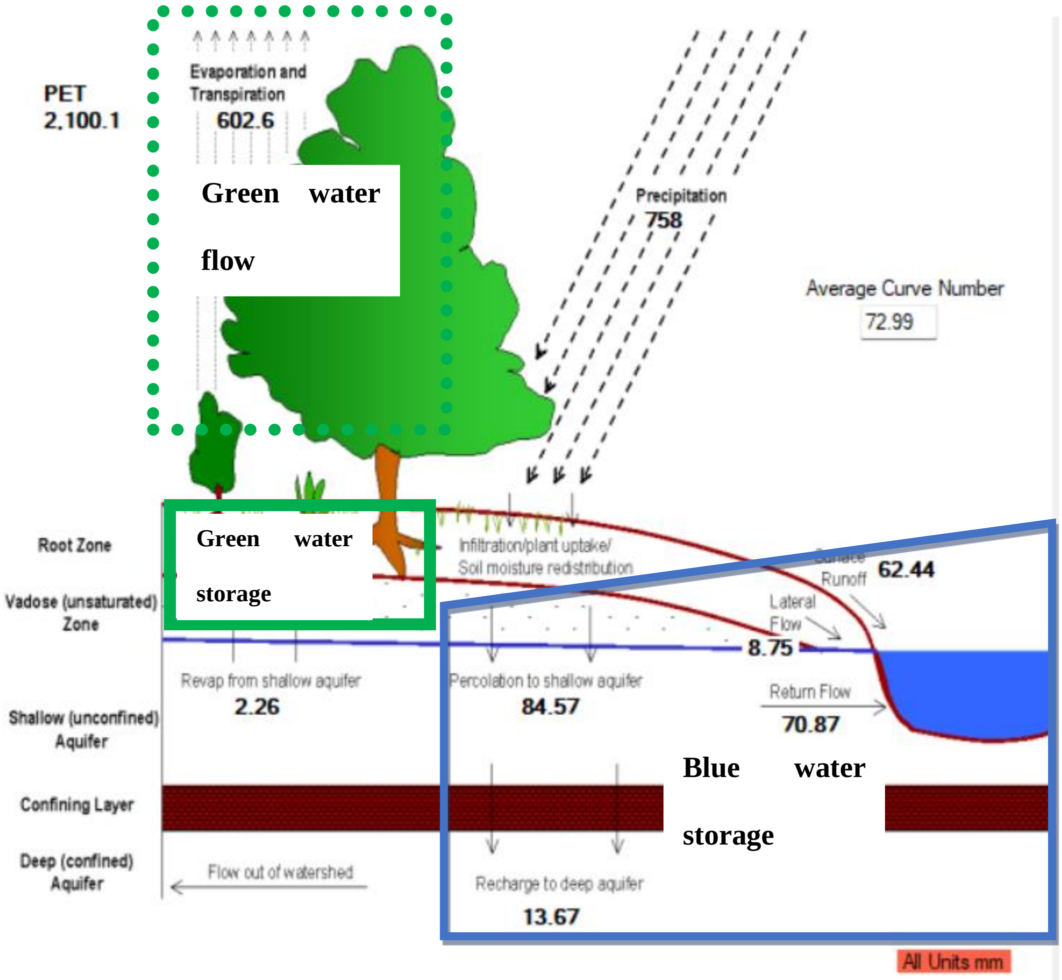


Figure 6-2: Conceptualisation of the Green-Blue water in SWAT

6.3.3 Evaluation of Nature-based Solutions (NbSs)

This study tested the performance of some of the NbSs that have the potential to reduce surface runoff and sediment load resulting from increased rainfall intensities, while increasing local blue water (especially dry season streamflow and groundwater) and productive green water (soil water storage and Evapotranspiration). Various NbSs recommended in Chapter five, involving conservation tillage with residue management, recharge structures and reforestation, including a 'combination of all these NbSs' scenarios were evaluated using scenario analysis. Apart from being recommended under Chapter three and five, conservation tillage and reforestation have also been suggested by various researchers in the study area (Collins et al. 2001, Chisola et al. 2020, Sichingabula et al. 2020).

The SWAT model allows for simulation of NbS practices and has extensively been used in literature in diverse environments for evaluation of best management practices (Tuppad et al., 2010, Arnold et al., 2012, Park et al., 2014, Hyandye et al., 2018, Pandey et al., 2021). In all these applications, significant flaws that could seriously invalidate its results are yet to be reported, although limitations exist as discussed under section 6.4.4. The rationale for the selected NbS is provided in the following sections.

6.3.5.1 Baseline scenario (Conventional tillage)

Conventional tillage is currently practiced in the catchment mainly using a mouldboard plough. Under this practice, the entire crop field is tilled. This tillage practice has widely been criticised as unstainable under the changing climate due to high sediment yields and loss of nutrients from the soil. In this study, the conventional tillage practice was modelled as the baseline upon which the performance of Nature-based Solutions (NbSs) on sediment load, including blue and green water was evaluated. The design parameters for this scenario in SWAT/SWAT-CUP are given in Table 6-1.

6.3.5.2 Conservation tillage

Conservation tillage is touted as having the potential to provide multiple benefits, not only in terms of soil and water conservation, but also socio-economic dividends by promoting increased crop yields or preventing crop failure in the event of longer dry spells (Rockström et al., 2009, Mihretie et al., 2022). It is seen as a practice of reducing soil loss, increasing soil water storage in the face of prolonged dry spells and helping to turn unproductive soil water evaporation to the more productive transpiration (Jewitt, 2006, Rockström et al., 2009, Falkenmark et al., 2014). Currently in Zambia, this practice represents a government and donor led initiative, but with the potential for communities to take a leading role.

Table 6-1: Design parameters for the Nature-based Solutions (NbSs) in SWAT/SWAT-CUP

NbS	Parameter	Parameter description	Designed values
Baseline (Conventional tillage with Mouldboard plough)	V__EFFMIX.till.dat	Mixing efficiency of tillage	0.95 (SWAT allowed range = 0-1)
	V__DEPTIL.till.dat	Depth of mixing caused by the tillage operation	150 mm (SWAT allowed range = 0-750 mm)
Conservation tillage	V__EFFMIX.till.dat	Mixing efficiency of tillage	0.30 (SWAT allowed range = 0-1)
	V__DEPTIL.till.dat	Depth of mixing caused by the tillage operation	100 mm (SWAT allowed range = 0-750 mm)
Reforestation	Conducted in ArcSWAT by changing the landcover map	Replace the crop and scrubland on higher slopes (slopes > 10%) with forest	Replaced original landcover map (forest area = 2%) with one where all slopes ≥ 10% had forest (forest area = 38%)
Recharge structures	V__CH_K1.sub	Effective hydraulic conductivity in tributary channel (mm hr^{-1})	25 (Default = 0, SWAT allowed range = 0-300)
	V__CH_N1.sub	Manning's "n" value for the tributary channels	0.08 (Default = 0.014, SWAT allowed range = 0.01-30)

Designed values based on SWAT user manual (Arnold et al., 2012), Tuppad and Srinivasan (2008), Hyandye et al. (2018) and Pandey et al. (2021)

V __ means the calibrated parameter value was replaced by a given value, R__ means the calibrated parameter value was multiplied by (1+ a given value)

The design of the conventional and conservation tillage operations in SWAT mainly differs by having different value ranges for the mixing efficiency of tillage (EFFMIX) and depth of mixing of the tillage operation (DEPTIL) as outlined in Table 6-1. The mixing efficiency value gives the proportion of residue and other materials such as nutrients and pesticides that are uniformly mixed within the soil depth of tillage given by DEPTIL, while the remaining fraction indicates the proportion of residue and nutrients that is left at the original location on the surface or soil layer (Arnold et al., 2012). In this study, conservation tillage was applied to all crop fields by changing the parameters as outlined in Table 6-1.

6.3.5.3 Recharge structures

To deal with the effects of climate change, rainwater harvesting will be important, especially in semi-arid areas. Installation of recharge structures will be key to storing rainwater underground in the rainy season, where it could be stored for longer periods. This could also help to increase groundwater availability for communities who often depend on boreholes for water supply like is often the case in meso-scale semi-arid catchments. The dolomitic/limestone nature of the geology in the case study catchment (upper Kaleya River Catchment) presents an opportunity for rainwater harvesting through groundwater recharge. This could also help to sustain the flows from the spring and support baseflow in general (Chisola et al., 2020, Chisola et al., 2022) as suggested by the findings from Chapters three and four.

Recharge structures could include recharge pits, infiltration wells, and check dams. A check dam is any barrier installed on the river or channel to make the water to pond, allow sediments to settle and the water to infiltrate so as to recharge the groundwater (Abbasi et al., 2019). In SWAT, recharge structures were implemented in subbasins with tributary channels. These were modelled by adjusting the effective hydraulic conductivity in tributary channel (CH_K1) and the Manning's "n" value for the tributary channels (CH_N1) [Table 6-1] as implemented in previous studies (Tuppad et al., 2010, Park et al., 2014, Pandey et al., 2021).

6.3.5.4 Reforestation

Reforestation is one of the most popular Nature-based Solutions (NbSs) that the government in Zambia and other stakeholders have been advocating for towards increased resilience to environmental change (GRZ, 2017). The Zambian government policy direction is to increase forest cover through reforestation and afforestation activities (GRZ, 2019). The communities are now encouraged to own or manage forests, and to promote natural regeneration of forest from which they could benefit through non-timber forest products such as honey, mushrooms, and carbon credits among others (Mfune, 2018, Chisola et al., 2020). In this study, reforestation was implemented assuming a case where all the cropland and scrublands on steep slopes (≥10%) are converted back to forest through farmer-assisted natural regeneration as discussed in Chisola et al. (2020) and in Chapter three. Additionally, the area around the spring was all converted to a large forest patch as proposed in Chapter three. These assumptions changed the forest area in the catchment from the current 2% for the baseline to 38% under reforestation (Figure 6-3 and Appendix 5-1).

6.3.5.5 Combination of various Nature-based Solutions (NbSs)

It is also widely recognised that a combination of NbSs may be required in semi-arid areas due to the higher heterogeneity of the landscape and eco-hydrological processes. Hence, this scenario assumed that all the NbSs in this study are implemented simultaneously. As such, conservation tillage was applied on all croplands, recharge structures were applied in subbasins with tributary channels, and reforestation was applied to steep slopes (≥10%) replacing cropland and scrubland.

6.3.5.6 Nature based solution scenario simulation

Each of the NbS scenarios under each climate change scenario (historical, RCP 4.5 and RCP 8.5) of the GCMs ensemble was run stochastically in SWAT-CUP premium. Thus, beyond its use for model calibration and validation, SWAT-CUP can be used for scenario modelling, including evaluation of best management practices, allowing the analyst to propagate the model parameter uncertainty in the analysis (Abbaspour et al., 2018, Abbaspour, 2022). However, the higher number of simulations [that is, five NbS scenarios by three ensemble scenarios (historical, RCP 4.5 and RCP 8.5) by several blue and green water components and sediment load] means that it was impossible to present all the results. Hence, only the results at the 50% uncertainty level (M95PPU) and/or hru file outputs are presented, analysed, and discussed in this Chapter.

6.3.5.7 Modelling and mapping the spatial distribution of sediment yields

In Kaleya, sediment yields were around 21 t km^{-2} $year^{-1}$ before for the 2000s, with other studies in the region reporting values less than 100 t km^{-2} $year^{-1}$ at the time (Sichingabula et al., 2000a). However, despite the figures appearing low, their impact on surface water availability particularly in reservoirs was found to be of major concern (Sichingabula et al., 2000a, Collins et al., 2001, Walling et al., 2001). Following increased cropland in the catchment, the sediment yield has more than doubled. To evaluate the spatial influence of various NbSs on sediment yields for better decision making, three erosion classes were created. These were noncritical (areas with specific sediment yields of 0 - 100 t km^{-2} $year^{-1}$), critical (areas with sediment yield of 100 - 200 t km^{-2} $year^{-1}$) and very critical (areas with sediment yield >200 t km^{-2} $year^{-1}$).

6.4 Results and discussion

6.4.1 Efficiency of nature-based solutions on blue and green water and sediment load management under various climate scenarios

The following sections report on the effectiveness of NbSs interventions in dealing with water availability and sediment load dynamics under various climate change scenarios.

6.4.2.1 Efficiency on blue water

Under the historical climate, all the NbS predicted reduced surface runoff, increased deep aquifer recharge and increased groundwater contribution to streamflow (Table 6-2 and Appendix 6-1). The combination of all NbS scenario predicted the largest changes in this regard under the historical climate scenario. Under this scenario, deep aquifer recharge was predicted to increase by 34%, while groundwater contribution (baseflow) to streamflow was predicted to increase by 19%. Surface runoff was predicted to reduce by 7%.

The reforestation NbS also predicted increased deep aquifer recharge (39%) and groundwater contribution to streamflow (baseflow) (11%) under the historical climate. Under reforestation, surface runoff was predicted to reduce by up to -74%. Recharge structures were the third most effective NbS in increasing deep aquifer recharge (3%) and groundwater contribution to streamflow (baseflow) (3%) under the historical climate. Both recharge structures and conservation tillage reduced surface runoff the least (-4%). Conservation tillage had almost no effect on deep aquifer recharge and baseflow contribution to streamflow (Appendix 6-1).

Under the RCP 4.5 climate scenario, reforestation was predicted to reduce surface runoff (69%) and increase deep aquifer recharge (23%) the most. But surprisingly, it also reduced groundwater contribution to streamflow slightly (2%) (Table 6-2 and Appendix 6-1). But under the RCP 8.5 scenario, reforestation still predicted a 2% increase in groundwater contribution to streamflow, and a deep aquifer recharge increase of 26%, following surface runoff reduction of 62%. These dynamics are further examined under section 6.4.2.3.

Under the projected climate scenarios, recharge structures were the most consistent in predicting increases in both deep aquifer recharge and groundwater (baseflow) contribution to streamflow both by 4% for both the RCP 4.5 and RCP 8.5 climate scenarios (Table 6-2). The combination of all NbS scenario also predicted a relatively higher increase in deep aquifer recharge (14%) and groundwater contribution to streamflow (2%), and a relatively higher reduction in surface runoff (-5%) for both RCP 4.5 and RCP 8.5 scenarios (Table 6-2 and Appendix 6-1). Again, apart from slightly reducing surface runoff, conservation tillage NbS had a negligible effect on both groundwater contribution to streamflow and on deep groundwater recharge under future climate change scenarios (Table 6-2 and Appendix 6-1).

6.4.2.2 Effectiveness on green water

The reforestation NbS predicted the highest increases in green water flow (amount of water drawn from shallow aquifer to plants/soil) by (117 – 260) % and actual evapotranspiration by (2 – 3) % under all climate change scenarios. The increases in ET were slightly higher under the RCP 4.5 and RCP 8.5 scenarios (Table 6-2 and Appendix 6-1). Recharge structures and conservation tillage had no effect on green water flow (Table 6-2). However, the combination of all the NbS predicted increased water flow from the shallow aquifer to plants by 26% under the historical climate, 13% under the RCP 4.5 climate and 11% under the RCP 8.5 climate scenario. Under the combination of all NbS scenario, the ET increased marginally by only 1% under all climate scenarios.

Table 6-2: Effects of Nature-based Solutions (NbSs) under various climate change scenarios

Climate change scenario	Water balance	Water type	Baseline	Recharge structures	Reforestation	Conservation tillage	Combination of all NbSs
			mm	% Change	% Change	% Change	% Change
Historical (average rainfall, 709 mm)	Surface runoff	Blue water	19	-4	-74	-4	-7
	Baseflow (Groundwater contribution to streamflow)	Blue water	90	3	11	0	19
	Shallow aquifer storage	Blue water	529	0	-26	0	0
	Deep aquifer recharge	Blue water flow	17	3	39	0	34
	Initial Soil moisture	Green water storage	131	0	-2	0	1
	REVAP (Water from shallow aquifer to plants/soil)	Green water flow	5	0	260	0	26
	Evapotranspiration	Green water flow	585	0	2	0	1
	Sediment load (tons $year^{-1}$)		1302	-35	-15	-4	-48
RCP 4.5 (average rainfall, 749 mm)	Surface runoff	Blue water	29	-4	-69	-1	-5
	Baseflow (Groundwater contribution to streamflow)	Blue water	116	4	-2	0	2
	Shallow aquifer storage	Blue water	532	0	-24	0	2
	Deep aquifer recharge	Blue water flow	22	4	23	0	14
	Initial Soil moisture	Green water storage	139	0	-8	0	1
	REVAP (Water from shallow aquifer to plants/soil)	Green water flow	9	0	121	0	13
	Evapotranspiration	Green water flow	588	0	3	0	1
	Sediment load (tons $year^{-1}$)		1832	-24	-7	-2	-34
RCP 8.5 (average rainfall, 788 mm)	Surface runoff	Blue water	40	-2	-62	0	-5
	Baseflow (Groundwater contribution to streamflow)	Blue water	139	4	2	0	2
	Shallow aquifer storage	Blue water	528	0	-24	0	2
	Deep aquifer recharge	Blue water flow	27	4	26	0	14
	Initial Soil moisture	Green water storage	136	0	-7	0	1
	REVAP (Water from shallow aquifer to plants/soil)	Green water flow	9	0	117	0	11
	Evapotranspiration	Green water flow	592	0	3	0	1
	Sediment load (tons $year^{-1}$)		2473	-15	-6	-1	-25

NbS - Nature based Solution, RCP – Representative Concentration Pathway

Generally, all the NbS predicted a very negligible positive effect (< 1%) on green water storage (soil moisture) (Appendix 6-1). Only the combination of all NbS scenario predicted increased soil moisture by up to 1% under all climate change scenarios (Table 6-2 and appendix 6-1).

Reforestation on the other hand predicted reduced green water storage (soil moisture) by up to -8% under the future climate. This unexpected result is further examined in section 6.4.2.3.

6.4.2.3 Examining the blue and green water dynamics

To better understand the blue and green water dynamics, the groundwater contribution to streamflow (baseflow) component of blue water and the soil moisture component of green water were examined. It was observed that in some subbasins there was predicted reduction in groundwater contribution to streamflow, while in others, there was an increase. The same was observed for soil moisture (Figure 6-3). Additionally, the increases in soil moisture and baseflow contribution appeared to have been mainly in areas where the reforested forest patches were larger (Figure 6-3). The increases and decreases at subbasin level cancelled each other, hence reforestation resulted in a net reduction in soil moisture and a small increase in baseflow contribution at a catchment scale as reported in Table 6-2 and Appendix 6-1. The net reduction in baseflow contribution by reforestation under the RCP 4.5 scenario compared to the RCP 8.5 scenario could be due to the higher plant water use from the shallow aquifer (RAVAP) (Table 6-2). This could be linked to the 1.5% increase in dry spell length under the RCP 4.5 scenario, while the same reduced under the RCP 8.5 scenario as reported in Chapter five.

6.4.2.4 Effectiveness of Nature-based Solutions in reducing sediment load

The highest predicted reduction in sediment load and yield was under the historical climate, followed by the RCP 4.5 scenario (Table 6-2 and Appendix 6-1). All the NbSs were lesser effective under the RCP 8.5 scenario. Among the individual NbSs, recharge structures reduced sediment load the most by about 35% under the historical climate, about 24% under the RCP

4.5 scenario and 15% under the RCP 8.5 scenario. Reforestation reduced sediment load by about 15% under historical climate, 7% and 6% under the RCP 4.5 and RCP 8.5 scenarios, respectively.

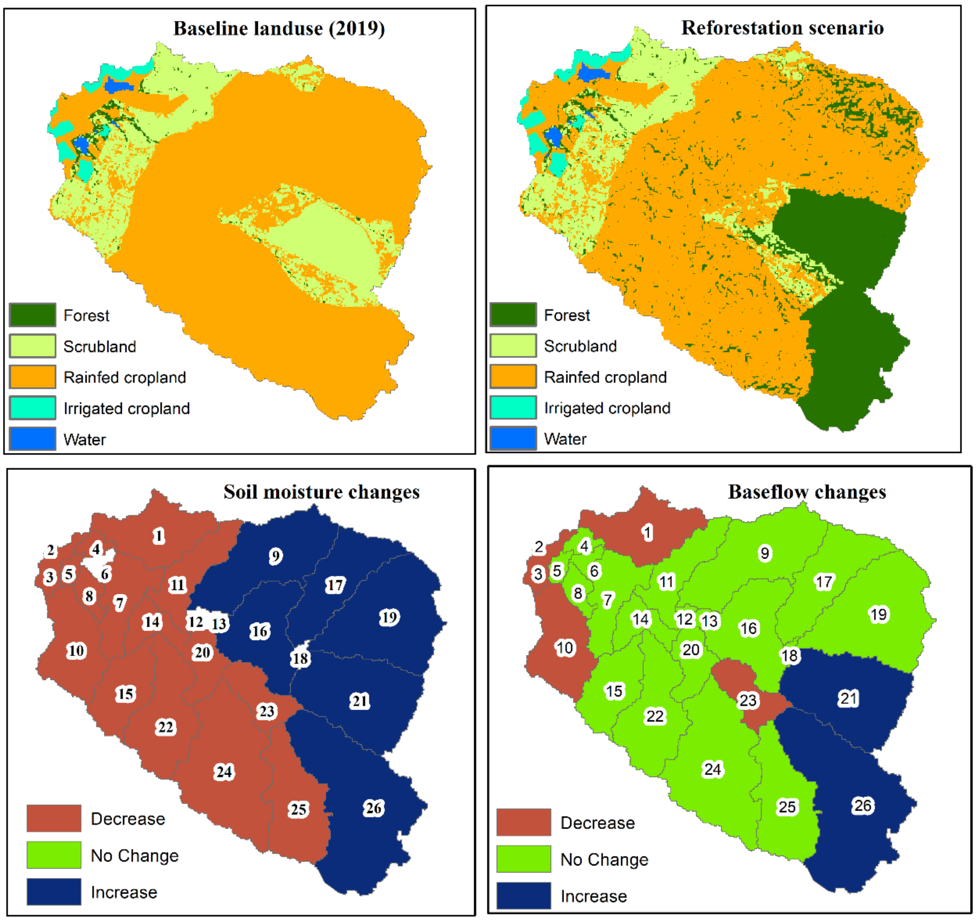


Figure 6-3: Soil moisture and Baseflow (Groundwater return flow [GW_Q]) dynamics under the baseline and reforestation landcover - RCP 8.5 scenario. *Numbers 1-26 indicate subbasin numbers.*

On the other hand, conservation tillage was mainly effective under the historical climate, reducing sediment load by about 4% under the historical climate, 2% under the RCP 4.5 climate and 1% under the RCP 8.5 climate scenario. The most effective reduction in sediment load was achieved when all the NbSs were implemented together (the combination of all NbSs scenario). This led to a 48% reduction in sediment load under the historical climate, including a 34% and 24% reduction under the RCP 4.5 and RCP 8.5 climate change scenarios, respectively. The magnitude of these changes in tonnes per year are given in Appendix 6-1.

It was noted that the predicted one-day rainfall intensity (RX1DAY) was higher than in the historical climate by 3% and 20% under the RCP 4.5 and RCP 8.5 scenarios, respectively (Chapter five). Additionally, there was a predicted 16% and 30% increase in the number of days with heavy rains (rainfall ≥ 10 mm) under the RCP 4.5 and RCP 8.5 scenarios, respectively. These increased intensities imply increased erosive power of rainfall in the future, hence reduced efficiency of NbSs interventions under the future climate scenarios, especially under the RCP 8.5, which had higher rainfall intensities and sediment load.

6.4.2.4.1 Spatial changes in sediment yield classes under various scenarios

The spatial extent influenced by each NbS are presented in Table 6-3. Recharge structures reduced the area of the catchment under the very critical sediment yield category from 66% to about 11% under the RCP 4.5 scenario and from about 88% to 43% under the RCP 8.5 climate change scenario (Table 6-3). This in turn increased the area under the noncritical sediment yield category under all climate change scenarios (Table 6-3).

Reforestation reduced the area under the critical sediment yield category from 66% to 63% of the catchment area under the historical climate. Reforestation also reduced the catchment area under very critical sediment yield category from 66% to 63% under the RCP 4.5 climate. Although reforestation had no impact on the spatial extent of each sediment yield category under the RCP 8.5 scenario, it reduced the average specific sediment yield in the very critical category from 339 t km^{-2} yr^{-1} to 309 t km^{-2} yr^{-1} (Table 6-3). Conservation tillage NbS predicted a reduced average specific sediment yield under the RCP 8.5 very critical sediment yield category from about 339 t km^{-2} yr^{-1} to 311 t km^{-2} yr^{-1}.

Table 6-3: Spatial influence of various Nature-based Solutions (NbSs) on sediment yield

Nature based solution (NbS)	Sediment yield class	Historical climate		RCP 4.5		RCP 8.5	
		Mean sediment yield (t/km^2/year)	Catchment Area (%)	Mean sediment yield (t/km^2/year)	Catchment Area (%)	Mean sediment yield (t/km^2/year)	Catchment Area (%)
Baseline (Pre NbS)	Very critical	-	0	247.8	65.95	339.1	87.87
	Critical	123.74	66.00	139.77	33.53	175.69	11.64
	Noncritical	63.41	34.00	81.8	0.51	99	0.49
Recharge structures	Very critical	-	0	212.13	10.7	275.6	42.61
	Critical	106.18	10.7	133.38	33.09	153.94	52.12
	Noncritical	44.15	89.3	72.74	56.22	98.84	5.27
Reforestation	Very critical	-	0	232.7	63.1	309.3	87.87
	Critical	114.2	62.90	139.77	36.49	175.69	11.64
	Noncritical	71.79	37.10	62.36	0.51	99	0.49
Conservation tillage	Very critical	-	0	251.1	65.94	311.0	87.87
	Critical	121.35	55.26	139.77	33.55	175.69	11.64
	Noncritical	63.41	44.74	64.23	0.51	99	0.49

Numbers 1-26 indicate subbasin numbers. RCP: Representative Concentration Pathway

6.4.2 Implications on the use of nature-based solutions for water resource management under a changing environment in semi-arid areas

All the NbS implemented in this study were meant to reduce surface runoff so that the rainwater is concentrated within the catchment for longer periods either as blue or green water. In this regard, all the NbS managed to reduce surface runoff. Reforestation reduced surface runoff the most and contributed to deep aquifer recharge the most, hence helping to store up the higher rainfall intensities within the catchment longer as groundwater.

As discussed in Chapter three, the presence of vegetation in the landscape slows down the movement of surface runoff and moderates the rain drop impact on the soil in the face of increasing rainfall intensities and dry spell length (Chisola et al., 2020). As such, reforestation using larger forest patches was recommended in Chapter three to augment wet season flows by supporting baseflow (Chisola et al., 2020). The modelling results of this NbS intervention in the current chapter generally support this idea based on the results under the historical and RCP 8.5 climate scenarios as can be perceived from section 6.4.2.3 and Figure 6-3, but also give a caution of the trade-offs that may need to be managed based on the results under the RCP 4.5 scenario.

For example, under the RCP 4.5 scenario, the results of the reforestation NbS were inconclusive in that although deep aquifer recharge increased, there was a slight reduction in groundwater contribution to streamflow, which would mean reduced streamflow in dry periods. This could be attributed to longer dry spells projected under the RCP 4.5 climate scenario (Chapter five), which would mean that more water would be taken out of the shallow aquifer to make up for ET deficits under the RCP 4.5 scenario than under the RCP 8.5 scenario as suggested by the REVAP values in Table 6-2.

Although the water taken out of the shallow aquifer to plants is highest under the historical climate, it could be noted that the ET is also lowest under this climate scenario possibly due to lower air temperatures (Chapter five). There is also a possibility of hydrological model uncertainties as the vegetation in the SWAT model may not be adequately responding to the projected climatic extremes, especially dry spells, and to elevated carbon dioxide in the atmosphere, which should ideally make plants to be more efficient in water use. This is further discussed under limitations in section 6.4.4.

Despite these uncertainties, the findings are consistent with previous experimental studies on the effects of forests on water yield in Zambia. In the only experimental study to date in Zambia, Mumeka (1986) observed an increase in annual streamflow in sub-catchments where trees removal was conducted. The increase in rainy season flows was attributed to increased runoff coefficient (surface runoff), while the increase in dry season flows was attributed to reduced ET after deforestation. This means, a reduction in surface runoff and increase in ET would be expected when regeneration of the forest takes place. However, the net effect would be increased baseflow contribution to streamflow and increased groundwater resources in areas with high infiltration capacity such as the upper Kaleya River Catchment as described in Chapters three and four and by (Chisola et al., 2022).

In general, the findings from this study lean more to the conclusion that reforestation (larger forest patches) could support baseflow as recommended in Chapter three, reduce surface runoff from higher rainfall intensities, thereby supporting recharge to the spring (Chapter four). The increased deep aquifer water could also be accessed through boreholes. This is important because most of the rural communities in semi-arid areas in the global south depend on deep groundwater through boreholes as these are cheaper than dam construction (Robins et al., 2006, Everard, 2015, Huang et al., 2019, Hoogesteger, 2022). Groundwater is also seen as being more resilient to climatic changes than surface water (MacDonald et al., 2011).

The predicted increasing green water flows (ET) from vegetation may not necessarily imply water losses. To the contrary, they may suggest increased ecosystem productivity in the catchment, using the water that would otherwise have been lost from the catchment to oceans and seas. The increased forest productivity (increased ET as proxy) could support alternative livelihood sources such as honey production, mushrooms, and caterpillar collection, grazing for livestock, and carbon credits. This could be through the market mechanisms discussed in Chapter three. This in turn could create multiple ecological and socio-economic co-benefits as surrounding communities can then derive the much-needed sustainable livelihoods from forest resources in the face of climate change as discussed in Chapter three. These other co-benefits could be explored in detail in future studies as a detailed investigation was out of the scope of this work.

Additionally, the findings in Figure 6-3 suggest that reforestation could be implemented in the subbasins where it has the potential for maintaining or increasing soil moisture and groundwater contribution to streamflow as a way of managing the trade-offs. For example, increased soil moisture storage increases productivity, while reduced sediment load reduces the risk of siltation of reservoirs meant to store rainwater. Improved water storage in reservoirs could help the dam owners to implement environmental flow releases to downstream reaches, thus improving hydrological connectivity as was the case before human activities increased in the Kaleya.

Recharge structures were the next most effective NbS in terms of managing rainfall by reducing surface runoff and increasing its storage as blue water deep aquifer recharge. Recharge structures by design trap the runoff, increasing infiltration into the ground, thereby recharging the groundwater, especially the deep aquifer. Since most of this water went to deep groundwater storage, there were negligible ET changes predicted under this scenario. Also, there was no vegetation to draw up water from the shallow aquifer, unlike under the reforestation NbS. In this regard, the recharge structures were also able to predict a more consistent increase in baseflow contribution to streamflow.

It is noted that apart from recharge structures such as infiltration pits implemented in this study, check dams could also be used. However, these could have similar negative effects on downstream dry season flows such as the current dams in the catchment. This could be addressed by provision of minimum flow bypass channels or pipes to provide sustained environmental flow downstream (Chisola et al., 2020) as recommended in Chapter three.

Although the benefits from improved tillage practices were negligible compared to those of other NbS, conservation tillage still had a positive effect on reducing sediment yield and slightly increased green water storage under the historical climate (Appendix 6-1). There was no change on green water storage (soil moisture) and groundwater possibly due to the slight increase in ET (Appendix 6-1). The slight increase in ET could have been due to crop residue retention that was implemented under conservation tillage practice. The slight increase in ET compensated for the slight reduction in surface runoff caused by the presence of crop residues. The results suggest that the retained soil water is immediately available and used by plants and crops to support their growth.

Therefore, conservation tillage offers an opportunity to maximize crop production and reduce soil loss in the face of increased rainfall extremes, and longer dry spells, and could help to reduce the need to open up new forest lands for farming (Falkenmark and Rockström, 2010, Wathum et al., 2016, Chisola et al., 2020). However, while conservation tillage practices have been promoted by government and donor agencies, farmers seem to retain the conventional tillage practices as they are perceived to be less labour intensive (Mfune et al., 2016).

Innovative financing mechanisms are needed if the implementation of nature-based solutions is to take off in semi-arid catchments of developing countries. Agricultural-based enterprises that incentivise farmers for successfully adopting improved tillage practices through market provision of products at premium prices, including value addition, could encourage the more widespread adoption of conservation tillage practices. In Zambia, such initiatives are mainly private sector-driven, with the Community Markets for Conservation (COMACO) taking a leading role and promising positive results have been recorded so far (Mfune et al., 2016). Other potential sources of funding for NbSs include water markets that could involve upstream versus downstream compensations among the water users, climate change financing mechanisms such as those under the United Nations Climate Change Conference of Parties (COP), and carbon credit markets among others.

Results also suggested that implementing different Nature-based Solutions (NbSs) simultaneously (combination of all the NbSs) could yield the best results for soil and water conservation. But the cost implications could restrict NbS selection and the needed combinations. Future studies could include a cost-benefit assessment of the NbSs, a more detailed search for models that could be used to make NbS interventions financially sustainable, and the piloting of these interventions on the actual landscape to derive further lessons on the benefits and limitations. These aspects were beyond the scope of this work.

With respect to managing sediment load, all the NbS were effective either as stand alone or in combination. Their effectiveness seemed to be a function of rainfall intensities, whereby the percentage reductions in sediment load were lower under the RCP 8.5, followed by the RCP 4.5 scenarios which have higher rainfall intensities in the same order. However, in magnitude terms with respect to tonnes per year, the reductions in sediment load were highest under the RCP 8.5 scenario (Appendix 6-1), showing that NbS could assist effectively in managing the future changes in sediment load. Reduced sediment load in turn could support efforts to keep stormwater longer in the catchment by sustaining the surface water storage capacities.

Considering global change, the results reaffirm the need for a paradigm shift whereby rainfall is seen as a primary resource for management as espoused by the green-blue water approach (Falkenmark and Rockström 2010). This could assist to build more resilient water catchments to support dependent livelihoods, including aquatic and terrestrial ecosystems in semi-arid areas. Nature-based Solutions (NbSs) such as reforestation, recharge structures and even conservation tillage with residue management have shown great potential to store up increased rainfall amounts and storm runoff within the sub-catchments as deep groundwater storage and contribute to baseflow, thereby supporting local blue water storage.

Further, the NbSs have shown potential to increase ecosystem productivity through increased beneficial green water flows using trapped rainwater and storm runoff which could have left the catchment in the first place if no interventions were done. The NbSs have also shown that they have the potential to deal with the negative effects of increased rainfall intensities on sediment yield.

6.4.3 Limitations

There is a question of how well the SWAT model simulates the NbS interventions, particularly those related to plant growth under the reforestation scenario and conservation tillage with residue management. Firstly. Among the sources of uncertainties are that the plant growth model in SWAT, may not be adequately capturing the changes in Leaf Area Index (LAI) in the rainy and dry seasons, and during longer dry spells which can result into crop failure, thereby affecting some hydrological processes (Zhang et al., 2020).

Further, the effects of elevated atmospheric carbon dioxide (eCO_2) in the context of the future climate were considered by adjusting the CO_2 in the future (RCP) scenarios. However, the vegetation/plants may not have been adequately responding to these changes in terms of becoming more water use efficient. Hence the higher withdrawal of water from the shallow aquifer to plants by the vegetation based NbSs could have contributed to their inconsistent effects on baseflow. Despite these limitations, the results generally fall within what is theoretically expected and are thus indicative of how various interventions could be evaluated before actual implementation in the landscape to better manage the partitioning of rainfall into blue and green water, and the trade-offs thereof for increased local water storage. In addition to improving the hydrological models, future work could include a more direct assessment of the likely socio-economic effects, which was outside the scope of this work.

6.5 Conclusions

Reforestation and recharge structures predicted reduced surface runoff generation and sediment load and increased deep blue water storage (deep groundwater). The predicted impacts of reforestation on baseflow were inconclusive, but generally pointed to increased baseflow contribution to streamflow. Reforestation and conservation tillage were important for beneficial green water flows owing to the predicted increase in evapotranspiration. Through the lenses of the green-blue water approach, this could mean increased ecosystem productivity at the local scale, using the storm water that could have been lost out of the catchment as overland flow.

The implementation of various nature-based solutions simultaneously could yield the best results in managing for green and blue water storage and reducing sediment load under different climate change scenarios. Although the effectiveness of the various NbS interventions appeared to decline percentage wise from the RCP 4.5 scenario to the RCP 8.5 scenario which had higher increase in rainfall intensities, in water depth and sediment tonnage terms, the positive effects were still substantial. It was concluded that nature-based solutions have potential for managing the partitioning of rainfall into blue and green water and reduce sediment load for increased local water storage under all climate change scenarios.

In summary, Chapter six integrated some of the major recommendations from Chapters three to five. The assessed recommendations are those that fall within the realm of NbSs due to their ability to generate multiple co-benefits needed for resilience. In this regard, Chapter six evaluated the extent to which the interventions proposed from Chapters three, four and five would still be effective in dealing with the future climatic and weather extremes (Figure 6-4) using the lenses of the ‘green-blue’ water approach. With this improved understanding of the climatic-landscape-hydrological interactions across temporal scales, the major conclusions, and recommendations are drawn in Chapter seven.

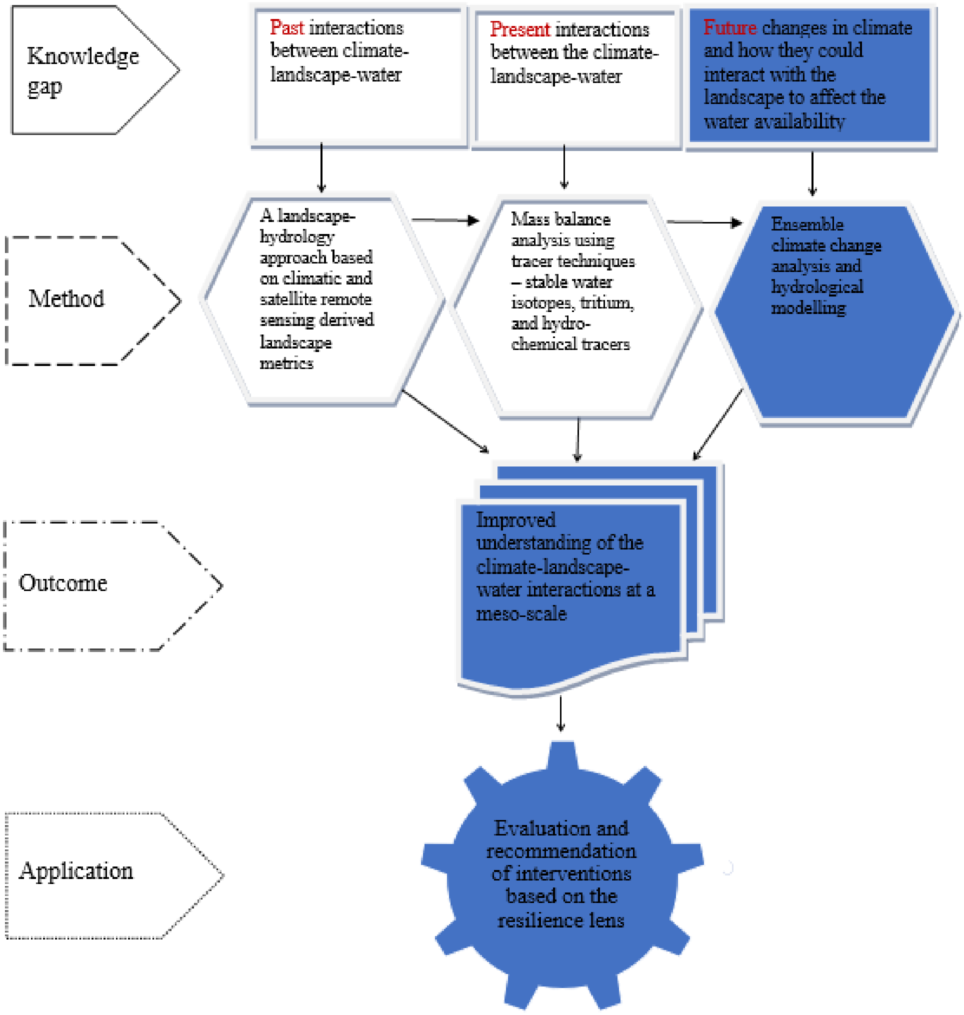


Figure 6-4: Analytical framework highlighting the focus for Chapter six

Chapter 7

Conclusions, recommendations, and contributions

A synthesis of the major findings and conclusions is provided. Recommendations and contributions of the thesis are also presented.

7.1 A synthesis of the climatic-landscape-hydrological interactions under global change

This PhD study used various tools to assess climatic-landscape-hydrological interactions of the past, present, and future. The goal was to unpack the key climatic and landscape pattern stressors on water availability and devise potential interventions to increase resilience of semi-arid sub-catchments under a changing environment.

Chapter three focused on the past interactions and addressed the first objective. The main research questions were: (1) What are the trends in seasonal climatic/weather, landcover composition and configuration patterns in the Kaleya River Catchment? (2) What are the main interactions among landscape components and climatic extremes that are important to inform landscape level water resource management interventions in a heterogeneous and fragmented catchment? The trend analysis results revealed that there is an increase in climatic and weather extremes towards increased rainfall intensities and variability, longer dry spells, late onset of rains, and increased air temperatures.

The landscape pattern indicated increasing fragmentation, agricultural intensification, and loss of forest land. Agricultural intensification has involved the expansion of both rainfed and irrigated cropland. Linked to this, is the increase in reservoirs in the landscape. From these climatic and landscape pattern changes, the results showed that the key drivers of declining streamflow regimes were increased rainfall intensity and variability, and ET on the climate side, and increased irrigated cropland, and reservoirs, particularly the patchiness of these landcovers in the landscape.

It was concluded that water resource interventions in the region must focus more on responding to the changing seasonal rainfall extremes than to annual rainfall totals. Further, the patchiness of cover in the landscape appeared to be more important than the percentage of a cover type in amplifying or reducing the effects of the changes in climatic and weather extremes. The Chapter recommended integrating various landscape configurations such as larger forest patches that can minimise impacts of some of the adversely changing climatic and weather extremes.

Chapter four focussed on present interactions and addressed the second objective. Here, the research question was on what sources may have dominant contributions to streamflow in a heterogenous semi-arid sub-catchment undergoing agricultural intensification such as the Kaleya River Catchment? Informed by the extent of landscape fragmentation in Chapter three, the water sampling considered spatial and temporal dynamics according to water use and seasonality (dry and wet season). This created the necessary homogeneity required for use of tracer-based techniques.

Results showed that storm water runoff and the spring were the major streamflow sources in the rainy season in the catchment. But in the dry season, the streamflow sources reflected a strong human intervention signal in which sources were different upstream and downstream. In the upper catchment, the spring was still a major streamflow source followed by irrigation return flow based on water from within the catchment. But this water was all intercepted by reservoirs in the middle catchment, hence downstream dry season streamflow sources were irrigation return flow and wastewater. The irrigation return flows downstream could be traced back to intra-basin water transfer (IBWT) from the Kafue River used for furrow irrigation of sugarcane in the lower Kaleya River Catchment.

The study recommended that there is need to improve irrigation efficiency but only in a way that ensures downstream flows can still be maintained. Water markets and improved socio-cooperate responsibility by Zambia Sugar Company could help to still maintain downstream flows in the lower Kaleya River from IBTW. Additionally, recharge to the spring upstream needs to be sustained while ensuring that minimum flow bypass pipes or channels are installed on reservoirs that are on the main river channel to improve water connectivity from the spring to downstream users.

Overall, the results of Chapter three and Chapter four indicated that irrigated agriculture has had contrasting effects on dry season flows depending on the source of water used for irrigation. Using the water from within the catchment, irrigated agriculture reduced dry season flows in the upper and middle catchment, despite some return flows in the upper catchment contributing to streamflow. But in the lower catchment, large scale irrigation increased dry season flows because of the intra-basin transfer water brought in from Kafue River, that ends up in the Kaleya River after irrigation, as an irrigation return flow.

Arising from the historical trends in observed climate and weather extremes in Chapter three and present climatic-landscape-hydrological dynamics in Chapter four, it was also necessary to evaluate the climate and weather extremes that must be anticipated in the future as predicted by global climate models for the area. Such a holistic assessment of the interactions would better inform water resource management interventions so that they have a long-lasting positive effect. A review of literature showed that there is a paucity of such studies at the micro- to meso-scale in sub–Saharan Africa.

Therefore, Chapter five focussed on the future interactions, addressing the third objective. Here, the research question was on how future climatic and weather extremes are likely to change at a local scale in the case study catchment and how their changes might affect water availability with respect to blue water flows (streamflow), green water flows (evapotranspiration) and sediment load. There was a further question on how landscape change might interact with the predicted changes in climate and weather extremes to affect water availability and sediment load. The uncertainties in the GCMs were considered by using a climate model ensemble, while the parameter uncertainty of the hydrological model used to evaluate the hydrological impacts was considered by taking a stochastic approach to model calibration and scenario analysis.

The GCMs predicted increased annual rainfall, mean and maximum air temperature by 2050. These were accompanied by increased rainfall intensities and dry spell length for both the RCP 4.5 and RCP 8.5 scenarios. These results were consistent with the patterns from historical observed climate data reported in Chapter three.

The climatic changes alone were predicted to increase streamflow and sediment load owing to higher rainfall amounts and rainfall intensities. But the higher sediment load could counter the positive effects of increased streamflow. Already, higher sediment load due to the higher erosive energy of rainfall are among the problems facing meso-scale semi-arid catchments, threatening surface water availability in these environments (Bisantino et al. 2011, Smetanova et al. 2020, Franchi et al. 2020).

Landcover change was predicted to reduce the positive effects of climate change and amplify the negative ones. It was predicted that landcover change would amplify the rainy season streamflow and sediment load and reduce green water storage (soil moisture) and dry season blue water flow (dry season streamflow), which climate change alone had predicted would increase. Therefore, Chapter five recommended that nature-based solutions are needed to capture the predicted increased rainfall, storm runoff (rainy season flows), and the resultant high sediment load so that storm water can be stored in the catchment longer, for use during the predicted longer dry spells.

Chapter six therefore evaluated the effectiveness of selected nature-based solutions in managing rainfall under various climate change scenarios and thus addressed objective four. The research question focussed on evaluating the extent to which nature-based solutions would be effective in managing the future climatic changes to increase green and blue water availability at a local scale. The study took the position that water resilience entails managing rainfall and its extremes to increase both green and blue water storage in sub catchments, while recognising the trade-offs that could ensue from partitioning of increased rainfall intensities into green and blue water.

Through the lenses of the green-blue water approach, selection of the nature-based solutions considered the importance of blue water, particularly groundwater and the huge role it plays in driving domestic and economic activities in semi-arid sub-catchments where most rivers are ephemeral. Added to this was a further recognition of green water, particularly soil moisture and beneficial evapotranspiration (transpiration) and the role it plays in biomass and food production, and in terrestrial ecosystems productivity, which in turn supports multiple livelihood types such as grazing, mushroom and caterpillar collection, bee keeping among others as these are necessary for community resilience to global change.

The findings in Chapter six predicted that reforestation and recharge structures could reduce surface runoff from increased rainfall intensities and channel a significant amount to deep ground water storage. Although the results were inconclusive in terms of baseflow contribution for the reforestation NbS under the RCP 4.5 scenario which had longer dry spell increases, the findings under the historical and RCP 8.5 climate scenarios predicted increased baseflow contribution which would help to increase dry season flows.

The inconsistent results under reforestation where attributed to increased green water flows through water withdrawal from the shallow aquifer to plants, and the eventual evapotranspiration. The general conclusion was that reforestation would increase baseflow contribution to streamflow going by the results under the historical and RCP 8.5 scenario, and under chapter three. However, the slight reduction in baseflow contribution under the RCP 4.5 scenario was also acknowledged as it could suggest that baseflow increases through reforestation may not be as straightforward under a changing climate, as some trade-offs between blue and green water would arise.

From a green-blue water perspective, the study argues that even if green water flows were to increase, this may not be a water loss as it could suggest increased ecosystem productivity locally, mostly using the water that could have been lost out of the catchment as overland flow if no intervention was done. Further, it was observed that there was still some notable increase in deep groundwater and a reduction in sediment load which would still augment the local blue water availability. The best results for water and soil conservation could however be achieved if all the nature-based solutions were implemented simultaneously. It was concluded that nature-based solutions have great potential for reducing storm runoff and sediment load arising from increased rainfall amounts and intensities, and can increase groundwater recharge, and green water. The specific findings of this PhD study are further summarised in Figure 7-1.

In general, the study concluded that improved understanding of the climatic-landscape-hydrological interactions of the past, present, and future at meso-scales can enhance our understanding of and adaptation to the adverse effects of global change towards more resilient sub-catchments in semi-arid areas. Through the green-blue water approach, the landscape patterns such as the patchiness of cover type which are not usually explicitly considered in catchment assessment methodologies, yet important to understand the interactions under a changing environment were brought to the fore. Through the same lenses, rainfall, and its changing characteristics (intensities) were viewed as a key resource that needs to be managed. Further green water was placed at the centre of the proposed management interventions as it is important for food and biomass production.

Climatic-landscape-hydrological interactions: Past, Present and Future

Past interactions

Results (Objective 1) showed that:

- increased rainfall intensity, & dry spell length & late onset of rains were major climatic stressors not seasonal rainfall totals.

- patchiness of a cover type was more important in explaining water availability than the percentage of cover type in the landscape.

- reforestation using larger forest patches could be used to manage seasonal flows.

Present interactions

Results (Objective 2) showed that:

- the spring is the primary source of water upstream, particularly during the dry season, but not downstream due to impoundments.

While irrigation explained decreasing dry season flows, net effect depended on source of irrigation water. Irrigation from other sources such as IBWT, could increase local streamflow through return flows.

Future interactions

Results (Objective 3) indicated:

- Predicted future climatic risks were increased rainfall amounts & intensity, extended dry spells, and increasing mean and maximum air temperatures.

- These could increase streamflow (potential flash flood risk), ET, and sediment loads.

- Landscape change would amplify some of the negative effects of climate change.

Proposed nature-based solutions to deal with future interactions

Results (Objective 4) predicted that:

- NbSs such as reforestation, recharge structures, and conservation tillage could help to manage the predicted increase in rainfall amounts and intensities and reduce storm water runoff/overland flow through increased storm water storage.

- the increased storm water storage locally could mainly be through increased blue water (particularly deep groundwater storage and baseflow) and green water (particularly beneficial ET useful in plant/ecosystem productivity), as well as indirectly through reduced sediment load.

- Increased rainfall intensities should be taken as a resource for improving resilience to other climatic shocks such as dry spells and increased rainfall variability. This could be achieved through the green-blue water approach implemented using nature-based solutions.

Figure 7-1: Some key messages from the study

7.2 Overall conclusion

The interactions of the changing landscape patterns with the changing climate and weather extremes and the effects on local green and blue water availability were investigated in this study. Overall, the study found that landscape pattern changes (patchiness of cover in addition to percentage of cover) amplify the negative effects of the changing climatic and weather extremes in the past, present, and future. But if well designed in form of NbS interventions, the landscape patterns could be used to manage the effects of climate change whereby the increasing rainfall intensities could be seen and managed as a resource for improving local water storage, and productivity thereby building resilience to other climatic extremes such as dry spells, rainfall variability and increasing air temperatures.

7.3 Limitations of the study and recommendations for future research

Detailed investigations into groundwater dynamics and use under a changing environment were beyond the scope of this work. Additionally, future studies can integrate assessment of socio-economic benefits that can be derived from NbSs implementation, assess community perceptions of the proposed NbSs interventions, including undertaking a cost benefit analysis of the NbSs.

7.4 Recommendations for improved water resources management

Other specific recommendations include:

1. Nature-based solutions such as farmer-assisted natural regeneration of forest patches towards larger forest patch sizes, are needed to enhance landscape hydrological processes that improve seasonal water availability. Other interventions could include

installation of recharge structures such as infiltration wells/pits and check dams in quick recharge areas of tributary sub-catchments to increase groundwater storage.

2. Agriculture in the catchment much invest in more efficient irrigation technology, such as drip and sprinkler irrigation. Since improving irrigation system efficiency could eliminate return flows which were found to be currently supplying dry season flows in the lower Kaleya River, there is need to keep the river flowing through minimum flow bypass channels/pipes from reservoirs upstream. This could be combined with a deliberate supply of IBTW from Kafue River to the lower Kaleya River which could be supported through a water market system.
3. Managing for increased soil moisture and groundwater recharge wherever the geology allows, could help to broaden the scope beyond streamflow and environmental flows to better include groundwater, which already plays an important role in meso-scale semi-arid catchments, and soil water needed by the terrestrial ecosystems, thus providing resilience to global change in a more holistic manner (Falkenmark and Rockström, 2010).

7.5 Contributions of the thesis

7.5.1 Contribution to the body of knowledge

The study has contributed to the body of knowledge in catchment hydrology in a less well studied part of the world, where landscape fragmentation and agricultural intensification (including irrigation), along with climate and weather extremes are on the increase. The study has teased out the important factors in the climatic-landscape-hydrological interactions that threaten local water availability at a meso-scale and how these interactions could be changed to increase local water storage.

7.5.2 Methodological contribution

The study conceptualised how data related to catchment hydrology under a changing environment should be collected, analysed, and applied. For this, the study applied a combination of various novel techniques such as partial least squares regression, stable water isotopes and hydro chemical tracers, ensemble climate modelling, and hydrological modelling (stochastically). As stand alone, these methodologies may not be adequate in understanding the changing regimes and drivers. In addition, a holistic approach was taken in terms of looking at the past-present-future and assessing the changes in terms of green and blue water. A further development of the assessment methodologies in catchment hydrology is recommended to keep pace with the evolving research questions under a changing environment. Presently, most hydrological models often used do not adequately capture the main processes especially with respect to plant/crop water use dynamics during dry spells and the patchiness of cover which are increasingly becoming important in process understanding under global change.

References

ABBASI, N. A., XU, X., LUCAS-BORJA, M. E., DANG, W. & LIU, B. 2019. The use of check dams in watershed management projects: Examples from around the world. *Science of The Total Environment,* 676**,** 683-691.

ABBASPOUR, K. C. 2015. SWAT-CUP: SWAT calibration and uncertainty programs—a user manual. *Eawag: Dübendorf, Switzerland***,** 16-70.

ABBASPOUR, K. C. 2022. The fallacy in the use of the "best-fit" solution in hydrologic modeling. *Science of The Total Environment,* 802**,** 149713.

ABBASPOUR, K. C., ROUHOLAHNEJAD, E., VAGHEFI, S., SRINIVASAN, R., YANG, H. & KLØVE, B. 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology,* 524**,** 733-752.

ABBASPOUR, K. C., VAGHEFI, S. A. & SRINIVASAN, R. 2018. A guideline for successful calibration and uncertainty analysis for soil and water assessment: A review of papers from the 2016 International SWAT Conference. Multidisciplinary Digital Publishing Institute.

ABIYE, T., MENGISTU, H., MASINDI, K. & DEMLIE, M. 2015. Surface water and groundwater interaction in the upper Crocodile River Basin, Johannesburg, South Africa: Environmental isotope approach. *South African Journal of Geology,* 118**,** 109-118.

AKAYOMBOKWA, I., VAN KOPPEN, B. & MATETE, M. 2017. Trends and outlook: Agricultural water management in Southern Africa. *Country Report Zambia. Colombo, Sri Lanka: Southern Africa Regional Program of the International Water Management Institute (IWMI). Accessed on,* 15.

AKINNIFESI, F. K. 2018. Africa's forest landscape restoration gathers momentum. *FAO Publication. Nature and Faune,* 32**,** 3-10.

ALBALAWNEH, A., CHANG, T.-K., HUANG, C.-W. & MAZAHREH, S. 2015. Using landscape metrics analysis and analytic hierarchy process to assess water harvesting potential sites in Jordan. *Environments,* 2**,** 415-434.

ALEXANDER, L. & HEROLD, N. 2016. ClimPACT2: Indices and software. User Mannual.

ALSTERHAG, E. & PETERSSON, L. 2004. Nutrient loading in the Kafue River between Mazabuka and Kafue Town, Zambia. *Uppsala University*.

AMIRI, B. J., GAO, J., FOHRER, N., ADAMOWSKI, J. & HUANG, J. 2019. Examining lag time using the landscape, pedoscape and lithoscape metrics of catchments. *Ecological Indicators,* 105**,** 36-46.

ARNOLD, J., KINIRY, J., SRINIVASAN, R., WILLIAMS, J., HANEY, E. & NEITSCH, S. 2012. Input/output documentation. *Soil and Water Assessment Tool. Texas Water Resources Institute. https://swat. tamu. edu/media/69296/swat-iodocumentation-2012. pdf*.

ARNOLD, J. G. & ALLEN, P. M. 1999. Automated methods for estimating baseflow and ground water recharge from streamflow records 1. *JAWRA Journal of the American Water Resources Association,* 35**,** 411-424.

ARNOLD, J. G., SRINIVASAN, R., MUTTIAH, R. S. & WILLIAMS, J. R. 1998. Large area hydrologic modeling and assessment part I: model development 1. *JAWRA Journal of the American Water Resources Association,* 34**,** 73-89.

BANZE, F., GUO, J. & XIAOTAO, S. 2018. Impact of climate change on precipitation in Zambeze River Basin in Southern Africa. *Nature Environment and Pollution Technology,* 17**,** 1093-1103.

BARROS, R., ISIDORO, D. & ARAGÜÉS, R. 2012. Three study decades on irrigation performance and salt concentrations and loads in the irrigation return flows of La Violada irrigation district (Spain). *Agriculture, ecosystems & environment,* 151**,** 44-52.

BECK, L. & BERNAUER, T. 2011. How will combined changes in water demand and climate affect water availability in the Zambezi river basin? *Global Environmental Change,* 21**,** 1061-1072.

BEGUERÍA, S., VICENTE-SERRANO, S. M., REIG, F. & LATORRE, B. 2014. Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *International Journal of Climatology,* 34**,** 3001-3023.

BELEMTOUGRI, A. P., DUCHARNE, A., TAZEN, F., OUDIN, L. & KARAMBIRI, H. 2021. Understanding key factors controlling the duration of river flow intermittency: Case of Burkina Faso in West Africa. *Journal of Hydrology: Regional Studies,* 37**,** 100908.

BERBEL, J., GUTIÉRREZ-MARTÍN, C. & EXPÓSITO, A. 2018. Impacts of irrigation efficiency improvement on water use, water consumption and response to water price at field level. *Agricultural Water Management,* 203**,** 423-429.

BETRU, T., TOLERA, M., SAHLE, K. & KASSA, H. 2019. Trends and drivers of land use/land cover change in Western Ethiopia. *Applied Geography,* 104**,** 83-93.

BOONGALING, C. G. K., FAUSTINO-ESLAVA, D. V. & LANSIGAN, F. P. 2018. Modeling land use change impacts on hydrology and the use of landscape metrics as tools for watershed management: The case of an ungauged catchment in the Philippines. *Land use policy,* 72**,** 116-128.

BRAUMAN, K. A., BREMER, L. L., HAMEL, P., OCHOA-TOCACHI, B. F., ROMAN-DAÑOBEYTIA, F., BONNESOEUR, V., ARAPA, E. & GAMMIE, G. 2022. Producing valuable information from hydrologic models of nature-based solutions for water. *Integrated environmental assessment and management,* 18**,** 135-147.

BROOKS, R. T. 2009. Potential impacts of global climate change on the hydrology and ecology of ephemeral freshwater systems of the forests of the northeastern United States. *Climatic Change,* 95**,** 469-483.

BROWN, D., CHANAKIRA, R. R., CHATIZA, K., DHLIWAYO, M., DODMAN, D., MASIIWA, M., MUCHADENYIKA, D., MUGABE, P. & ZVIGADZA, S. 2012. *Climate change impacts, vulnerability and adaptation in Zimbabwe*, International Institute for Environment and Development. IIED Climate Change Working Paper No. 3, October 2012, London.

BUGAN, R. D., JOVANOVIC, N. Z. & DE CLERCQ, W. P. 2012. The water balance of a seasonal stream in the semi-arid Western Cape (South Africa). *Water Sa,* 38**,** 201-212.

BURNS, D. A. 2002. Stormflow-hydrograph separation based on isotopes: the thrill is gone—what's next? *Hydrological Processes,* 16**,** 1515-1517.

BUTCHER, J. B., JOHNSON, T. E., NOVER, D. & SARKAR, S. 2014. Incorporating the effects of increased atmospheric CO2 in watershed model projections of climate change impacts. *Journal of Hydrology,* 513**,** 322-334.

BUTTLE, J. 1994. Isotope hydrograph separations and rapid delivery of pre-event water from drainage basins. *Progress in Physical Geography,* 18**,** 16-41.

BUTTLE, J. M. & MCDONNELL, J. J. 2005. Isotope tracers in catchment hydrology in the humid tropics. *In:* BRUIJNZEEL, L. A. & BONELL, M. (eds.) *Forests, Water and People in the Humid Tropics: Past, Present and Future Hydrological Research for Integrated Land and Water Management.* Cambridge: Cambridge University Press.

CALLIARI, E., STACCIONE, A. & MYSIAK, J. 2019. An assessment framework for climate-proof nature-based solutions. *Science of The Total Environment,* 656**,** 691-700.

CAMACHO, S. V., SARAIVA, O. A., WENNINGER, J. & UHLENBROOK, S. 2015. Understanding runoff processes in a semi-arid environment through isotope and hydrochemical hydrograph separations. *Hydrology and Earth System Sciences,* 19**,** 4183-4199.

CARRASCAL, L. M., GALVÁN, I. & GORDO, O. 2009. Partial least squares regression as an alternative to current regression methods used in ecology. *Oikos,* 118**,** 681-690.

CARRERA, J., VÁZQUEZ-SUÑÉ, E., CASTILLO, O. & SÁNCHEZ-VILA, X. 2004. A methodology to compute mixing ratios with uncertain end-members. *Water Resources Research,* 40.

CECCHI, P., FORKUOR, G., COFIE, O., LALANNE, F., POUSSIN, J.-C. & JAMIN, J.-Y. 2020. Small reservoirs, landscape changes and water quality in sub-Saharan West Africa. *Water,* 12**,** 1967.

CHANG, C.-Y. 2021. Special issue: Local landscape planning and management in rural areas. *Landscape and Ecological Engineering,* 17**,** 295-298.

CHEN, Y., XU, C., CHEN, Y., LIU, Y. & LI, W. 2013. Progress, challenges and prospects of eco-hydrological studies in the Tarim river basin of Xinjiang, China. *Environmental management,* 51**,** 138-153.

CHIANG, L.-C., CHUANG, Y.-T. & HAN, C.-C. 2019. Integrating Landscape Metrics and Hydrologic Modeling to Assess the Impact of Natural Disturbances on Ecohydrological Processes in the

Chenyulan Watershed, Taiwan. *International Journal of Environmental Research and Public Health*, 16**,** 266.

CHIRWA, P. W., SYAMPUNGANI, S. & GELDENHUYS, C. J. 2014. Managing southern African woodlands for biomass production: The potential challenges and opportunities. *Bioenergy from Wood.* In: Seifert, T. (eds) Bioenergy from Wood. Managing Forest Ecosystems, vol 26. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-7448-3_4. Accessed on 12/03/2021.

CHISANGA, C. B., MUBANGA, K. H., SICHIGABULA, H., BANDA, K., MUCHANGA, M., NCUBE, L., VAN NIEKERK, H. J., ZHAO, B., MKONDE, A. A. & RASMENI, S. K. 2022. Modelling climatic trends for the Zambezi and Orange River Basins: implications on water security. *Journal of Water and Climate Change*, 13**,** 1275-1296.

CHISOLA, M. N. & KURÁŽ, M. 2016. Patterns and Implications of Hydrologic Regime Change in Chongwe River, Zambia. *Journal of Geography and Geology,* 8**,** 1.

CHISOLA, M. N., VAN DER LAAN, M. & BRISTOW, K. L. 2020. A landscape hydrology approach to inform sustainable water resource management under a changing environment. A case study for the Kaleya River Catchment, Zambia. *Journal of Hydrology: Regional Studies,* 32**,** 100762.

CHISOLA, M. N., VAN DER LAAN, M. & BUTLER, M. J. 2022. Quantifying streamflow sources to improve water allocation management in a catchment undergoing agricultural intensification. *Physics and Chemistry of the Earth, Parts A/B/C,* 128**,** 103227.

CHOMBA, C. I. 2017. Sedimentation and its effects on selected small dams in Lusaka Province, Zambia. University of Zambia, MSs Thesis.

CHRISTOPHERSEN, N. & HOOPER, R. P. 1992. Multivariate analysis of stream water chemical data: The use of principal components analysis for the end-member mixing problem. *Water Resources Research,* 28**,** 99-107.

CHRISTOPHERSEN, N., NEAL, C., HOOPER, R. P., VOGT, R. D. & ANDERSEN, S. 1990. Modelling streamwater chemistry as a mixture of soilwater end-members. A step towards second-generation acidification models. *Journal of Hydrology(Amsterdam),* 116**,** 307-320.

CLARK, I. D. & FRITZ, P. 1997. *Environmental isotopes in hydrogeology,* CRC press.

CLARK, M. P., SLATER, A. G., RUPP, D. E., WOODS, R. A., VRUGT, J. A., GUPTA, H. V., WAGENER, T. & HAY, L. E. 2008. Framework for Understanding Structural Errors (FUSE): A modular framework to diagnose differences between hydrological models. *Water Resources Research,* 44.

COHEN-SHACHAM, E., WALTERS, G., JANZEN, C. & MAGINNIS, S. 2016. Nature-based solutions to address global societal challenges. *IUCN: Gland, Switzerland,* 97**,** 2016-2036.

COLLIER, M. J. & BOURKE, M. The case for mainstreaming nature-based solutions into integrated catchment management in Ireland. Biology and Environment: Proceedings of the Royal Irish Academy, 2020. JSTOR, 107-113.

COLLINS, A., WALLING, D., SICHINGABULA, H. & LEEKS, G. 2001. Suspended sediment source fingerprinting in a small tropical catchment and some management implications. *Applied Geography,* 21**,** 387-412.

CONWAY, D., VAN GARDEREN, E. A., DERYNG, D., DORLING, S., KRUEGER, T., LANDMAN, W., LANKFORD, B., LEBEK, K., OSBORN, T. & RINGLER, C. 2015. Climate and southern Africa's water–energy–food nexus. *Nature Climate Change,* 5**,** 837-846.

CORREA, A., WINDHORST, D., TETZLAFF, D., CRESPO, P., CÉLLERI, R., FEYEN, J. & BREUER, L. 2017. Temporal dynamics in dominant runoff sources and flow paths in the A ndean P áramo. *Water Resources Research,* 53**,** 5998-6017.

DEWALLE, D. R., SWISTOCK, B. R. & SHARPE, W. E. 1988. Three-component tracer model for stormflow on a small Appalachian forested catchment. *Journal of Hydrology,* 104**,** 301-310.

DING, J., JIANG, Y., LIU, Q., HOU, Z., LIAO, J., FU, L. & PENG, Q. 2016. Influences of the land use pattern on water quality in low-order streams of the Dongjiang River basin, China: A multi-scale analysis. *Science of the Total Environment,* 551-552**,** 205-16.

DU, J., JIA, Y., HAO, C., QIU, Y., NIU, C. & LIU, H. 2019. Temporal and spatial changes of blue water and green water in the Taihang Mountain Region, China, in the past 60 years. *Hydrological Sciences Journal,* 64**,** 2040-2056.

DUMONT, A., MAYOR, B. & LÓPEZ-GUNN, E. 2013. Is the rebound effect or Jevons paradox a useful concept for better management of water resources? Insights from the irrigation modernisation process in Spain. *Aquatic procedia,* 1**,** 64-76.

EASTERLING, W. E., ROSENBERG, N. J., MCKENNEY, M. S., JONES, C. A., DYKE, P. T. & WILLIAMS, J. 1992. Preparing the erosion productivity impact calculator (EPIC) model to simulate crop response to climate change and the direct effects of CO2. *Agricultural and Forest Meteorology,* 59**,** 17-34.

EKNESS, P. & RANDHIR, T. O. 2015. Effect of climate and land cover changes on watershed runoff: A multivariate assessment for storm water management. *Journal of Geophysical Research: Biogeosciences,* 120**,** 1785-1796.

EKNESS, P. A. 2013. *Ecohydrologic impacts of climate and land use changes on watershed systems: a multi-scale assessment for policy.* Doctoral dissertation, University of Massachusetts Amherst.

EPTING, S. M. 2016. *Using landscape metrics to predict hydrologic connectivity patterns between forested wetlands and streams in a coastal plain watershed.* Doctoral dissertation, University of Maryland, College Park.

EVERARD, M. 2015. Community-based groundwater and ecosystem restoration in semi-arid north Rajasthan (1): Socio-economic progress and lessons for groundwater-dependent areas. *Ecosystem Services,* 16**,** 125-135.

FAGGIAN, P. 2021. Future Precipitation Scenarios over Italy. *Water,* 13**,** 1335.

FALKENMARK, M., JÄGERSKOG, A. & SCHNEIDER, K. 2014. Overcoming the land–water disconnect in water-scarce regions: time for IWRM to go contemporary. *International Journal of Water Resources Development,* 30**,** 391-408.

FALKENMARK, M. & ROCKSTRÖM, J. 2006. The new blue and green water paradigm: Breaking new ground for water resources planning and management. *Journal of water resources planning and management,* 132**,** 129-132.

FALKENMARK, M. & ROCKSTRÖM, J. 2010. Building Water Resilience in the Face of Global Change: From a Blue-Only to a Green-Blue Water Approach to Land-Water Management. *Journal of Water Resources Planning and Management,* 136**,** 606-610.

FALKENMARK, M., ROCKSTROM, J. & ROCKSTRÖM, J. 2004. *Balancing water for humans and nature: the new approach in ecohydrology. ,* London, Earthscan.

FARJAD, B., POOYANDEH, M., GUPTA, A., MOTAMEDI, M. & MARCEAU, D. 2017. Modelling Interactions between Land Use, Climate, and Hydrology along with Stakeholders' Negotiation for Water Resources Management. *Sustainability,* 9**,** 2022.

FARRÉS, M., PLATIKANOV, S., TSAKOVSKI, S. & TAULER, R. 2015. Comparison of the variable importance in projection (VIP) and of the selectivity ratio (SR) methods for variable selection and interpretation. *Journal of Chemometrics,* 29**,** 528-536.

FERGUSON, B. K. 1991. Landscape hydrology, a component of landscape ecology. *Journal of Environmental Systems,* 21**,** 193-205.

FIERING, M. B. & HOLLING, C. 1974. Management and standards for perturbed ecosystems. *Agro-ecosystems,* 1**,** 301-321.

FOVET, O., BELEMTOUGRI, A., BOITHIAS, L., BRAUD, I., CHARLIER, J. B., COTTET, M., DAUDIN, K., DRAMAIS, G., DUCHARNE, A. & FOLTON, N. 2021. Intermittent rivers and ephemeral streams: Perspectives for critical zone science and research on socio-ecosystems. *Wiley Interdisciplinary Reviews: Water,* 8**,** e1523.

FRANK, I. E. 1987. Intermediate least squares regression method. *Chemometrics and Intelligent Laboratory Systems,* 1**,** 233-242.

FU, B.-J., ZHAO, W.-W., CHEN, L.-D., LIU, Z.-F. & LÜ, Y.-H. 2005. Eco-hydrological effects of landscape pattern change. *Landscape and Ecological Engineering,* 1**,** 25-32.

GANNON, C., KANDY, D., TURNER, J., KUMAR, I., PILLI-SIHVOLA, K. & CHANDA, F. S. 2014. Nearterm climate change in Zambia. *Red Cross/Red Crescent Climate Centre, The Hague*.

GAYE, C. B. & TINDIMUGAYA, C. 2019. Challenges and opportunities for sustainable groundwater management in Africa. *Hydrogeology Journal,* 27**,** 1099-1110.

GEBREMICAEL, T. G., MOHAMED, Y. A. & VAN DER ZAAG, P. 2019. Attributing the hydrological impact of different land use types and their long-term dynamics through combining parsimonious hydrological modelling, alteration analysis and PLSR analysis. *Science of The Total Environment,* 660**,** 1155-1167.

GERMAN, L. A., HEPINSTALL-CYMERMAN, J., BIGGS, T., PARKER, L. & SALINAS, M. 2020. The environmental effects of sugarcane expansion: A case study of changes in land and water use in southern Africa. *Applied Geography,* 121**,** 102240.

GRAFTON, R. Q. & WHEELER, S. A. 2018. Economics of water recovery in the Murray-Darling Basin, Australia. *Annual Review of Resource Economics,* 10**,** 487-510.

GRAHAM, L. P., ANDERSSON, L., HORAN, M., KUNZ, R., LUMSDEN, T., SCHULZE, R., WARBURTON, M., WILK, J. & YANG, W. 2011. Using multiple climate projections for assessing hydrological response to climate change in the Thukela River Basin, South Africa. *Physics and Chemistry of the Earth, Parts A/B/C,* 36**,** 727-735.

GRZ 2008. Zambia Integrated water resources management and water efficiency implementation plan. Volume 1: Main report (2007 – 2030). . *Government Republic of Zambia, Lusaka*.

GRZ 2011. Government Republic of Zambia (GRZ), The water resources management act. no 21 of 2011 15th April, 2011 ed. Lusaka, Zambia: Government Republic of Zambia (GRZ).

GRZ. 2015a. *Soils Map of Zambia*. Chilanga, Mount Makulu Research Station: Government Republic of Zambia. .

GRZ 2015b. Soils of Zambia. Chilanga: Mount Makulu Soil research unit.

GRZ 2017. National investment plan to reduce deforestation and forest degradation (2018-2022). Lusaka: Government Republic of Zambia (GRZ), Ministry of Lands and Natural Resources.

GRZ 2019. Zambia land degradation neutrality national report. Lusaka: Goverment Republic of Zambia, Ministry of Water Development, Sanitation and Environmental Protection

GRZ 2020. Third national communication to the United Nations Framework Convention on Climate Change (UNFCCC). Lusaka, Zambia: Ministry of Lands and Natural Resources.

GUPTA, J. & VAN DER ZAAG, P. 2008. Interbasin water transfers and integrated water resources management: Where engineering, science and politics interlock. *Physics and Chemistry of the Earth, Parts A/B/C,* 33**,** 28-40.

GUZHA, A. C., RUFINO, M. C., OKOTH, S., JACOBS, S. & NÓBREGA, R. L. B. 2018. Impacts of land use and land cover change on surface runoff, discharge and low flows: Evidence from East Africa. *Journal of Hydrology: Regional Studies,* 15**,** 49-67.

HABETS, F., MOLÉNAT, J., CARLUER, N., DOUEZ, O. & LEENHARDT, D. 2018. The cumulative impacts of small reservoirs on hydrology: A review. *Science of The Total Environment,* 643**,** 850-867.

HACHIGONTA, S., REASON, C. & TADROSS, M. 2008. An analysis of onset date and rainy season duration over Zambia. *Theoretical and applied climatology,* 91**,** 229-243.

HANDAVU, F., SYAMPUNGANI, S. & CHISANGA, E. 2011. The influence of stump diameter and height on coppicing ability of selected key Miombo woodland tree species of Zambia: A guide for harvesting for charcoal production. *Journal of Ecology and the Natural Environment,* 3**,** 461-468.

HARGREAVES, G. H. 1994. Defining and using reference evapotranspiration. *Journal of Irrigation and Drainage Engineering,* 120**,** 1132-1139.

HAROU, J. J., MATTHEWS, J. H., SMITH, D. M., MCDONNELL, R. A., BORGOMEO, E., SARA, J. J., BRAECKMAN, J. P., MATTHEWS, N., DALTON, J. & YOUNG, M. D. Water at COP25: Resilience enables climate change adaptation through better planning, governance and finance. Proceedings of the Institution of Civil Engineers-Water Management, 2020. Thomas Telford Ltd, 55-58.

HATTERMANN, F. F., HUANG, S. & KOCH, H. 2014. Climate change impacts on hydrology and water resources in Germany. *Meteorologische Zeitschrift,* 10**,** 201-211.

HER, Y., YOO, S.-H., CHO, J., HWANG, S., JEONG, J. & SEONG, C. 2019. Uncertainty in hydrological analysis of climate change: multi-parameter vs. multi-GCM ensemble predictions. *Scientific reports,* 9**,** 1-22.

HEROLD, M., MAYAUX, P., WOODCOCK, C. E., BACCINI, A. & SCHMULLIUS, C. 2008. Some challenges in global land cover mapping: An assessment of agreement and accuracy in existing 1 km datasets. *Remote Sensing of Environment,* 112**,** 2538-2556.

HOBBS, R. J. 1993. Effects of landscape fragmentation on ecosystem processes in the Western Australian wheatbelt. *Biological conservation,* 64**,** 193-201.

HOEKSTRA, A. Y,(2003) Virtual Water Trade. Proceedings of the international Expert Meeting on Virtual Water Trade. Delft University: Netherlands, 2002.

HOEKSTRA, A. Y., CHAPAGAIN, A. K., MEKONNEN, M. M. & ALDAYA, M. M. 2011. *The water footprint assessment manual: Setting the global standard,* London, Earthscan.

HOFF, H. 2009. Challenges in upland watershed management: The Green-Blue Water approach. *Managing Water Resources in a Time of Global Change.* London: Earthscan.

HOFF, J. 2015. 'Think globally, act locally': Climate change mitigation and citizen participation. *Community Governance and Citizen-Driven Initiatives in Climate Change Mitigation.* London: Earthscan from Routledge.

HOLLING, C. S. 1973. Resilience and stability of ecological systems. *Annual review of ecology and systematics,* 4**,** 1-23.

HOOGESTEGER, J. 2022. Regulating agricultural groundwater use in arid and semi-arid regions of the Global South: Challenges and socio-environmental impacts. *Current Opinion in Environmental Science & Health,* 27**,** 100341.

HOOPER, R. P. 2003. Diagnostic tools for mixing models of stream water chemistry. *Water Resources Research,* 39**,** 1055-68.

HOOPER, R. P. 2015. End member mixing analysis (EMMA) spreadsheet. http://www.cof.orst.edu/cof/fe/watershd/Documents/Shortcourses/shortcourse/ShortcourseEMMA/index.htm. Accessed on 26/11/2020.

HOOPER, R. P., CHRISTOPHERSEN, N. & PETERS, N. E. 1990. Modelling streamwater chemistry as a mixture of soilwater end-members—An application to the Panola Mountain catchment, Georgia, USA. *Journal of Hydrology,* 116**,** 321-343.

HRACHOWITZ, M., BOHTE, R., MUL, M. L., BOGAARD, T. A., SAVENIJE, H. H. G. & UHLENBROOK, S. 2011. On the value of combined event runoff and tracer analysis to improve understanding of catchment functioning in a data-scarce semi-arid area. *Hydrology and Earth System Sciences,* 15**,** 2007-2024.

HUANG, F., ZHANG, Y., ZHANG, D. & CHEN, X. 2019. Environmental Groundwater Depth for Groundwater-Dependent Terrestrial Ecosystems in Arid/Semiarid Regions: A Review. *International Journal of Environmental Research and Public Health,* 16**,** p.763.

HUGHES, D. A. 2006. Water resources estimation in less developed regions—issues of uncertainty associated with. *Predictions in Ungauged Basins: Promise and Progress,* 303**,** p.72.

HUGHES, D. A., JEWITT, G., MAHÉ, G., MAZVIMAVI, D. & STISEN, S. 2015. A review of aspects of hydrological sciences research in Africa over the past decade. *Hydrological Sciences Journal,* 60**,** 1865-1879.

HUGHES, D. A. & MANTEL, S. K. 2010. Estimating the uncertainty in simulating the impacts of small farm dams on streamflow regimes in South Africa. *Hydrological Sciences Journal,* 55**,** 578-592.

HUGHES, D. A., TSHIMANGA, R. M., TIRIVAROMBO, S. & TANNER, J. 2014. Simulating wetland impacts on stream flow in southern Africa using a monthly hydrological model. *Hydrological Processes,* 28**,** 1775-1786.

HYANDYE, C. B., WORQUL, A., MARTZ, L. W. & MUZUKA, A. N. 2018. The impact of future climate and land use/cover change on water resources in the Ndembera watershed and their mitigation and adaptation strategies. *Environmental Systems Research,* 7**,** 1-24.

IFRC 2022. Zambia: Floods in Namwala and Ndola districts, Operation update n° 01 (MDRZM015). International Federation of Red Cross And Red Crescent Societies. https://reliefweb.int/report/zambia/zambia-floods-namwala-and-ndola-districts-operation-update-n-01-mdrzm015#:~:text=Most%20parts%20of%20Zambia%20started,to%20

tropical%20storm%20(ANA). Accessed 09/10/2022.

JACOB, D., PODZUN, R. & CLAUSSEN, M. REMO—A model for climate research and weather prediction. International workshop on limited-area and variable resolution models, Beijing, China, 1995. 273-278.

JAMES, A. L. & ROULET, N. T. 2006. Investigating the applicability of end-member mixing analysis (EMMA) across scale: A study of eight small, nested catchments in a temperate forested watershed. *Water Resources Research,* 42**,** 1-17.

JEWITT, G. 2006. Integrating blue and green water flows for water resources management and planning. *Physics and Chemistry of the Earth, Parts A/B/C,* 31**,** 753-762.

JHA, M., ARNOLD, J. G., GASSMAN, P. W., GIORGI, F. & GU, R. R. 2006. Climate change sensitivity assessment on upper Mississippi River Basin streamflows using swat *JAWRA Journal of the American Water Resources Association,* 42**,** 997-1015.

JHA, P. & SCHMIDT, S. 2021. State of biofuel development in sub-Saharan Africa: How far sustainable? *Renewable and Sustainable Energy Reviews,* 150**,** 111432.

JONATHAN DAVIES, STEFANO BARCHIESI, CLAIRE J. OGALI, REBECCA WELLING, JAMES DALTON & LABAN, P. 2016. Water in drylands. Adapting to scarcity through integrated management. *IUCN: Gland, Switzerland***,** 44 pages.

KATTAN, Z. 2008. Estimation of evaporation and irrigation return flow in arid zones using stable isotope ratios and chloride mass-balance analysis: Case of the Euphrates River, Syria. *Journal of Arid Environments,* 72**,** 730-747.

KEESSTRA, S., NUNES, J., NOVARA, A., FINGER, D., AVELAR, D., KALANTARI, Z. & CERDÀ, A. 2018. The superior effect of nature based solutions in land management for enhancing ecosystem services. *Science of the Total Environment,* 610**,** 997-1009.

KENNEDY, V., KENDALL, C., ZELLWEGER, G. W., WYERMAN, T. A. & AVANZINO, R. 1986. Determination of the components of stormflow using water chemistry and environmental isotopes, Mattole River basin, California. *Journal of Hydrology,* 84**,** 107-140.

KEYS, P. W. & FALKENMARK, M. 2018. Green water and African sustainability. *Food Security,* 10**,** 537-548.

KLAUS, J. & MCDONNELL, J. 2013. Hydrograph separation using stable isotopes: Review and evaluation. *Journal of Hydrology,* 505**,** 47-64.

KLING, H., STANZEL, P. & PREISHUBER, M. 2014. Impact modelling of water resources development and climate scenarios on Zambezi River discharge. *Journal of Hydrology: Regional Studies,* 1**,** 17-43.

KOENIGER, P., HAMUTOKO, J., POST, V. E. A., BEYER, M., GAJ, M., HIMMELSBACH, T. & WANKE, H. 2020. Evaporation loss along the Calueque-Oshakati Canal in the Cuvelai-Etosha Basin (Northern Namibia): evidence from stable isotopes and hydrochemistry. *Isotopes in Environmental and Health Studies***,** 1-14.

KUMAR, N., TISCHBEIN, B., KUSCHE, J., LAUX, P., BEG, M. K. & BOGARDI, J. J. 2017. Impact of climate change on water resources of upper Kharun catchment in Chhattisgarh, India. *Journal of Hydrology: Regional Studies,* 13**,** 189-207.

KUSANGAYA, S., WARBURTON, M. L., ARCHER VAN GARDEREN, E. & JEWITT, G. P. W. 2014. Impacts of climate change on water resources in southern Africa: A review. *Physics and Chemistry of the Earth, Parts A/B/C,* 67-69**,** 47-54.

LAFORTEZZA, R., CHEN, J., VAN DEN BOSCH, C. K. & RANDRUP, T. B. 2018. Nature-based solutions for resilient landscapes and cities. *Environmental research,* 165**,** 431-441.

LE ROUX, B., VAN DER LAAN, M., VAHRMEIJER, T., BRISTOW, K. L. & ANNANDALE, J. G. 2017. Establishing and testing a catchment water footprint framework to inform sustainable irrigation water use for an aquifer under stress. *Science of the Total Environment,* 599**,** 1119-1129.

LEE, S., YEO, I.-Y., SADEGHI, A. M., MCCARTY, G. W., HIVELY, W. D., LANG, M. W. & SHARIFI, A. 2018. Comparative analyses of hydrological responses of two adjacent watersheds to climate variability and change using the SWAT model. *Hydrology & Earth System Sciences,* 22.

LETA, O. T., EL-KADI, A. I., DULAI, H. & GHAZAL, K. A. 2016. Assessment of climate change impacts on water balance components of Heeia watershed in Hawaii. *Journal of Hydrology: Regional Studies,* 8**,** 182-197.

LOCH, A. & ADAMSON, D. 2015. Drought and the rebound effect: a Murray–Darling Basin example. *Natural Hazards,* 79**,** 1429-1449.

LUOGA, E. J., WITKOWSKI, E. & BALKWILL, K. 2004. Regeneration by coppicing (resprouting) of miombo (African savanna) trees in relation to land use. *Forest Ecology and Management,* 189**,** 23-35.

MACDONALD, A., BONSOR, H., CALOW, R., TAYLOR, R., LAPWORTH, D., MAURICE, L., TUCKER, J. & O DOCHARTAIGH, B. 2011. Groundwater resilience to climate change in Africa. Nottinghamshire: British Geological Survey, 32pp.

MAGAND, C., ALVES, M. H., CALLEJA, E., DATRY, T., DÖRFLINGER, G., ENGLAND, J., GALLART, F., GÓMEZ, R., JORDA-CAPDEVILA, D. & MARTÍ, E. 2020. Intermittent rivers and ephemeral streams: what water managers need to know. Technical report – Cost ACTION CA 15113.10.5281/zenodo.3888474. https://digital.csic.es/handle/10261/214789. Accessed on 23/04/2022.

MAGILLIGAN, F. J. & NISLOW, K. H. 2001. LONG-TERM CHANGES IN REGIONAL HYDROLOGIC REGIME FOLLOWING IMPOUNDMENT IN A HUMID-CLIMATE WATERSHED 1. *JAWRA Journal of the American Water Resources Association,* 37**,** 1551-1569.

MAGILLIGAN, F. J. & NISLOW, K. H. 2005. Changes in hydrologic regime by dams. *Geomorphology,* 71**,** 61-78.

MALMER, A., MURDIYARSO, D., BRUIJNZEEL, L. & ILSTEDT, U. 2010. Carbon sequestration in tropical forests and water: a critical look at the basis for commonly used generalizations. *Global Change Biology,* 16**,** 599-604.

MARTÍN, G. E., COSTA, M. M. & MÁÑEZ, S. K. 2020. An operationalized classification of Nature Based Solutions for water-related hazards: From theory to practice. *Ecological Economics,* 167**,** 106460.

MATCHAYA, G., NHAMO, L., NHLENGETHWA, S. & NHEMACHENA, C. 2019. An Overview of Water Markets in Southern Africa: An Option for Water Management in Times of Scarcity. *Water,* 11**,** 1006.

MCGARIGAL, K., CUSHMAN, S. & ENE, E. 2012. FRAGSTATS v4: Spatial pattern analysis program for categorical and continuous maps. University of Massachusetts, Amherst, MA, USA. http://www.umass.edu/landeco/research/fragstats/fragstats. Accessed on 03/02/2020.

MCGARIGAL, K. & MARKS, B. J. 1995. FRAGSTATS: spatial analysis program for quantifying landscape structure. *USDA Forest Service General Technical Report PNW-GTR-351*.

MEHMOOD, T. 2016. Hotelling T2 based variable selection in partial least squares regression. *Chemometrics and Intelligent Laboratory Systems*, 154**,** 23-28.

MEHMOOD, T., LILAND, K. H., SNIPEN, L. & SÆBØ, S. 2012. A review of variable selection methods in Partial Least Squares Regression. *Chemometrics and Intelligent Laboratory Systems,* 118**,** 62-69.

MEIGH, J. The impact of small farm reservoirs on urban water supplies in Botswana. Natural Resources Forum, 1995. Oxford, UK: Blackwell publishing limited, 71-83.

MEINHARDT, M., FLEISCHER, M., FINK, M., KRALISCH, S., KENABATHO, P., DE CLERCQ, W., ZIMBA, H., PHIRI, W. & HELMSCHROT, J. 2018. Semi-arid catchments under change: adapted hydrological models to simulate the influence of climate change and human activities on rainfall-runoff processes in southern Africa. *Biodiversity and Ecology,* 6**,** 114-130.

MEVIK, B.-H. & WEHRENS, R. 2007. The pls package: principal component and partial least squares regression in R. *Journal of Statistical software,* 18**,** 1-23.

MFUNE, O. 2018. Towards ‘private forests’ in Zambia: opportunities, possibilities and risks. *FAO Publication. Nature and Faune,* 32**,** 11-15.

MFUNE, O., CHISOLA, M. N. & ZIBA, I. 2016. How Can Multifunctional Agriculture Support a Transition to a Green Economy in Africa? Lessons from the COMACO Model in Zambia. *Agriculture,* 6**,** 48.

MIHRETIE, F. A., TSUNEKAWA, A., HAREGEWEYN, N., ADGO, E., TSUBO, M., EBABU, K., MASUNAGA, T., KEBEDE, B., MESHESHA, D. T., TSUJI, W., BAYABLE, M. & BERIHUN, M. L. 2022. Tillage and crop management impacts on soil loss and crop yields in northwestern Ethiopia. *International Soil and Water Conservation Research,* 10**,** 75-85.

MILEHAM, L., TAYLOR, R., TODD, M., THOMPSON, J. & TINDIMUGAYA, C. 2009. Climate change impacts on the terrestrial hydrology of a humid, equatorial catchment: Sensitivity of projections to rainfall intensity. *Hydrological Sciences Journal,* 54**,** 727-738.

MOKUA, R. A., GLENDAY, J., NEL, J. & BUTLER, M. 2020. Combined use of stable isotopes and hydrochemical characteristics to determine streamflow sources in the Jonkershoek catchment, South Africa. *Isotopes in Environmental and Health Studies,* 56**,** 238-259.

MORIASI, D. N., ARNOLD, J. G., VAN LIEW, M. W., BINGNER, R. L., HARMEL, R. D. & VEITH, T. L. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE,* 50**,** 885-900.

MOSS, R. H., EDMONDS, J. A., HIBBARD, K. A., MANNING, M. R., ROSE, S. K., VAN VUUREN, D. P., CARTER, T. R., EMORI, S., KAINUMA, M., KRAM, T., MEEHL, G. A., MITCHELL, J. F. B., NAKICENOVIC, N., RIAHI, K., SMITH, S. J., STOUFFER, R. J., THOMSON, A. M., WEYANT, J. P. & WILBANKS, T. J. 2010. The next generation of scenarios for climate change research and assessment. *Nature,* 463**,** 747-756.

MUBANGA, K. H. & UMAR, B. B. Climate Variability and Change in Southern Zambia: 1910 to 2009. 2014 International Conference on Intelligent Agriculture (ICOIA), 2014. 94-100.

MUCHANGA, M., SICHINGABULA, H. M., OBANDO, J., CHOMBA, I., SIKAZWE, H. & CHISOLA, M. 2019. Bathymetry of the Makoye Reservoir and its Implications on Water Security for Livestock within the Catchment. *International Journal of Geography and Geology,* 8**,** 93-109.

MUCHELENG'ANGA, C., TURTON, A., MBAWO, E., NG'OMA, M., MUKUBESA, L. & MUSONDA, W. Water Demand Management. Natural Resource Reconstruction and Social Adaptive Capacity: A Case Study from Chongwe-Chalimbana Area of Zambia. In the Proceedings of the WISA 2002 Biennial Conference, Durban, 2002. 19-23.

MULENGA, B. P., WINEMAN, A. & SITKO, N. J. 2017. Climate Trends and Farmers' Perceptions of Climate Change in Zambia. *Environmental Management,* 59**,** 291-306.

MULETA, T. T. & BIRU, M. K. 2019. Human modified landscape structure and its implication on ecosystem services at Guder watershed in Ethiopia. *Environmental monitoring and assessment,* 191**,** 295.

MUMEKA, A. 1986. Effect of deforestation and subsistence agriculture on runoff of the Kafue River headwaters, Zambia. *Hydrological sciences journal,* 31**,** 543-554.

MUPANGWA, W., WALKER, S. & TWOMLOW, S. 2011. Start, end and dry spells of the growing season in semi-arid southern Zimbabwe. *Journal of Arid Environments,* 75**,** 1097-1104.

NAVARRO-RACINES, C. E. & TARAPUES, J. 2015. Bias-correction in the CCAFS-Climate Portal: A description of methodologies. Cali, Colombia: International Center for Tropical Agriculture (CIAT). https://hdl.handle.net/10568/76609. Accessed on 23/03/2021.

NDESO-ATANGA, A. 2018. Creating a forest landscape restoration movement in Africa: A call to heal planet Earth. *Nature and Faune (FAO/UNEP) eng v. 32 (1)*.

NEWMAN, B. D., WILCOX, B. P., ARCHER, S. R., BRESHEARS, D. D., DAHM, C. N., DUFFY, C. J., MCDOWELL, N. G., PHILLIPS, F. M., SCANLON, B. R. & VIVONI, E. R. 2006. Ecohydrology of water-limited environments: A scientific vision. *Water Resources Research,* 42.

NGOMA, H., HAMUDUDU, B., HANGOMA, P., SAMBOKO, P., HICHAAMBWA, M. & KABAGHE, C. 2017. Irrigation Development for Climate Resilience in Zambia: The Known Knowns and Known Unknowns. *Report, Indaba Agricultural Policy Research Institute (IAPRI).* Lusaka: Indaba Agricultural Policy Research Institute (IAPRI), Zambia.

NHEMACHENA, C., NHAMO, L., MATCHAYA, G., NHEMACHENA, C. R., MUCHARA, B., KARUAIHE, S. T. & MPANDELI, S. 2020. Climate Change Impacts on Water and Agriculture Sectors in Southern Africa: Threats and Opportunities for Sustainable Development. *Water*, 12**,** 2673.

NKHUWA, D. C., MWEEMBA, C. & KABIKA, J. 2013. Country Water Resources Profile for Zambia. *unpublished report, University of Zambia, http://nepadwatercoe. org/resources/nepad-water-coescountry-water-resource-profiles/(accessed 30 January 2014)*.

OGUNKOYA, O. O. & JENKINS, A. 1993. Analysis of storm hydrograph and flow pathways using a three-component hydrograph separation model. *Journal of Hydrology,* 142**,** 71-88.

OLSSON, J., ARHEIMER, B., BORRIS, M., DONNELLY, C., FOSTER, K., NIKULIN, G., PERSSON, M., PERTTU, A.-M., UVO, C. B. & VIKLANDER, M. 2016. Hydrological climate change impact assessment at small and large scales: key messages from recent progress in Sweden. *Climate,* 4**,** 39.

PANDEY, A., BISHAL, K., KALURA, P., CHOWDARY, V., JHA, C. & CERDÀ, A. 2021. A soil water assessment tool (SWAT) modeling approach to prioritize soil conservation management in river basin critical areas coupled with future climate scenario analysis. *Air, Soil and Water Research,* 14.

PARK, J.-Y., YU, Y.-S., HWANG, S.-J., KIM, C. & KIM, S.-J. 2014. SWAT modeling of best management practices for Chungju dam watershed in South Korea under future climate change scenarios. *Paddy and Water Environment,* 12**,** 65-75.

PARK, Y., KIM, Y., PARK, S.-K., SHIN, W.-J. & LEE, K.-S. 2018. Water quality impacts of irrigation return flow on stream and groundwater in an intensive agricultural watershed. *Science of The Total Environment,* 630**,** 859-868.

PARSONS, D., STERN, D. & STERN, R. Making Multilevel Data Ideas More Accessible. Proceedings of the IASE Satellite Conference" Teaching Statistics in a Data Rich World, 2017.

PATAKAMURI, S. K., O'BRIEN, N. & PATAKAMURI, M. S. K. 2017. Package 'modifiedmk'. *Cran. R-project*.

PELIZARDI, F., BEA, S. A., CARRERA, J. & VIVES, L. 2017. Identifying geochemical processes using End Member Mixing Analysis to decouple chemical components for mixing ratio calculations. *Journal of Hydrology,* 550**,** 144-156.

PEÑA-ARANCIBIA, J. L., BRUIJNZEEL, L. A., MULLIGAN, M. & VAN DIJK, A. I. J. M. 2019. Forests as 'sponges' and 'pumps': Assessing the impact of deforestation on dry-season flows across the tropics. *Journal of Hydrology,* 574**,** 946-963.

PENG, Y., WANG, Q., WANG, H., LIN, Y., SONG, J., CUI, T. & FAN, M. 2019. Does landscape pattern influence the intensity of drought and flood? *Ecological Indicators,* 103**,** 173-181.

PERRY, C. 2007. Efficient irrigation; inefficient communication; flawed recommendations. *Irrigation and Drainage: The journal of the International Commission on Irrigation and Drainage,* 56**,** 367-378.

PERRY, C., STEDUTO, P., ALLEN, R. G. & BURT, C. M. 2009. Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. *Agricultural Water Management,* 96**,** 1517-1524.

PHILLIPS, D. L. & GREGG, J. W. 2001. Uncertainty in source partitioning using stable isotopes. *Oecologia,* 127**,** 171-179.

PIERNA, J. A. F., ABBAS, O., BAETEN, V. & DARDENNE, P. 2009. A Backward Variable Selection method for PLS regression (BVSPLS). *Analytica chimica acta,* 642**,** 89-93.

PRINSLOO, C. & MATEMA, T. 2021. Optimising agricultural value chains in southern Africa after. Available: https://www.africaportal.org/publications/optimising-agricultural-value-chains-southern-africa-after-covid-19/ [Accessed 16/11/2021].

PURVIS, L. & DINAR, A. 2020. Are intra-and inter-basin water transfers a sustainable policy intervention for addressing water scarcity? *Water Security,* 9**,** 100058.

QURESHI, M., SCHWABE, K., CONNOR, J. & KIRBY, M. 2010. Environmental water incentive policy and return flows. *Water Resources Research,* 46.

RAYMOND, C. M., BREIL, M., NITA, M., KABISCH, N., DE BEL, M., ENZI, V., FRANTZESKAKI, N., GENELETTI, G., LOVINGER, L. & CARDINALETTI, M. 2017. *An impact evaluation framework to support planning and evaluation of nature-based solutions projects. Report prepared by the EKLIPSE Expert Working Group on Nature-Based Solutions to Promote Climate Resilience in Urban Areas*, Centre for Ecology and Hydrology, University of Oxford.

REANEY, S. M. 2022. Spatial targeting of nature-based solutions for flood risk management within river catchments. *Journal of Flood Risk Management***,** p.e12803.

RIDDELL, E., EVERSON, C., CLULOW, A. & MENGISTU, M. 2013. The hydrological characterisation and water budget of a South African rehabilitated headwater wetland system. *Water SA,* 39**,** 57-66.

ROBINS, N., DAVIES, J., FARR, J. & CALOW, R. 2006. The changing role of hydrogeology in semi-arid southern and eastern Africa. *Hydrogeology Journal,* 14**,** 1483-1492.

ROCKSTRÖM, J. & FALKENMARK, M. 2000. Semiarid crop production from a hydrological perspective: gap between potential and actual yields. *Critical reviews in plant sciences*, 19**,** 319-346.

ROCKSTRÖM, J., FALKENMARK, M., ALLAN, T., FOLKE, C., GORDON, L., JÄGERSKOG, A., KUMMU, M., LANNERSTAD, M., MEYBECK, M. & MOLDEN, D. 2014. The unfolding water drama in the Anthropocene: towards a resilience-based perspective on water for global sustainability. *Ecohydrology,* 7**,** 1249-1261.

ROCKSTRÖM, J., KAUMBUTHO, P., MWALLEY, J., NZABI, A. W., TEMESGEN, M., MAWENYA, L., BARRON, J., MUTUA, J. & DAMGAARD-LARSEN, S. 2009. Conservation farming strategies in East and Southern Africa: Yields and rain water productivity from on-farm action research. *Soil and Tillage Research,* 103**,** 23-32.

ROUHANI, H. & JAFARZADEH, M. S. 2018. Assessing the climate change impact on hydrological response in the Gorganrood river basin, Iran. *Journal of Water and Climate Change,* 9**,** 421-433.

SADC, S. A. D. C.-. 2019. Synthesis Report on the State of Food and Nutrition Security and Vulnerability in Southern Africa. *SADC RVAA Programme.* Windhoek, Namibia: SADC.

SAKEYO, E. 2008. Modelling the impact of deforestation on the stream flows-A case of Chalimbana river catchment in Chongwe, Zambia. Tema vatten i natur och samhälle.

SARAIVA OKELLO, A. M. L., UHLENBROOK, S., JEWITT, G. P., MASIH, I., RIDDELL, E. S. & VAN DER ZAAG, P. 2018. Hydrograph separation using tracers and digital filters to quantify runoff components in a semi-arid mesoscale catchment. *Hydrological Processes,* 32**,** 1334-1350.

SCHEUMANN, W. & PHIRI, G. 2018. Coordination–the Key to Governing the Water-Land-Food Nexus in Zambia? *Deutsches Institut für Entwicklungspolitik gGmbHTulpenfeld 6, 53113 Bonn*.

SCHINDLER, D. W. 1997. Widespread effects of climatic warming on freshwater ecosystems in North America. *Hydrological Processes,* 11**,** 1043-1067.

SCHINDLER, D. W. 2001. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. *Canadian Journal of Fisheries and Aquatic Sciences,* 58**,** 18-29.

SCHRÖDER, B. 2006. Pattern, process, and function in landscape ecology and catchment hydrology ? how can quantitative landscape ecology support predictions in ungauged basins (PUB)? *Hydrology and Earth System Sciences,* 10**,** 967-979.

SCHWABE, K., NEMATI, M., LANDRY, C. & ZIMMERMAN, G. 2020. Water Markets in the Western United States: Trends and Opportunities. *Water,* 12**,** 233.

SCHYNS, J. F., HOEKSTRA, A. Y., BOOIJ, M. J., HOGEBOOM, R. J. & MEKONNEN, M. M. 2019. Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy. *Proceedings of the National Academy of Sciences,* 116**,** 4893-4898.

SCOTT, C. A., VICUÑA, S., BLANCO-GUTIÉRREZ, I., MEZA, F. & VARELA-ORTEGA, C. 2014. Irrigation efficiency and water-policy implications for river basin resilience. *Hydrol. Earth Syst. Sci.,* 18**,** 1339-1348.

SEDDON, N., CHAUSSON, A., BERRY, P., GIRARDIN, C. A., SMITH, A. & TURNER, B. 2020a. Understanding the value and limits of nature-based solutions to climate change and other global challenges. *Philosophical Transactions of the Royal Society B,* 375**,** p.20190120.

SEDDON, N., DANIELS, E., DAVIS, R., CHAUSSON, A., HARRIS, R., HOU-JONES, X., HUQ, S., KAPOS, V., MACE, G. M., RIZVI, A. R., REID, H., ROE, D., TURNER, B. & WICANDER, S. 2020b. Global recognition of the importance of nature-based solutions to the impacts of climate change. *Global Sustainability,* 3**,** e15.

SEMBA, M., NDEBELE-MURISA, M., MUBAYA, C. P., KIMIREI, I. A., CHAVULA, G., MWEDZI, T., MUTIMUKURU-MARAVANYIKA, T. & ZENDA, S. 2020. *Historical and Future Climate Scenarios of the Zambezi River Basin, in Ecological Changes in the Zambezi River Basin,* Dakar, Senegal, Council for the Development of Social Science Research in Africa.

SEN, P. K. 1968. Estimates of the regression coefficient based on Kendall's tau. *Journal of the American statistical association,* 63**,** 1379-1389.

SERDECZNY, O., ADAMS, S., BAARSCH, F., COUMOU, D., ROBINSON, A., HARE, W., SCHAEFFER, M., PERRETTE, M. & REINHARDT, J. 2017. Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. *Regional Environmental Change,* 17**,** 1585-1600.

SHAKACITE, O., CHUNGU, D., NG'ANDWE, P., CHENDAUKA, B., SIAMPALE, A., TAVANI, R., ROBERTS, W. & VESA, L. 2016. Integrated land use assessment phase II – report for Zambia. The Food and Agriculture Organization of the United Nations and the Forestry Department, Ministry of Lands and Natural Resources, Lusaka, Zambia. Viewed at www. zmb-nfms. org/iluaii/index. php. Accessed om 23/02/2020.

SHI, Z., AI, L., LI, X., HUANG, X., WU, G. & LIAO, W. 2013. Partial least-squares regression for linking land-cover patterns to soil erosion and sediment yield in watersheds. *Journal of Hydrology,* 498**,** 165-176.

SIBANDA, S., GRAB, S. & AHMED, F. 2018. Spatio-temporal temperature trends and extreme hydro-climatic events in southern Zimbabwe. *South African Geographical Journal,* 100**,** 210-232.

SICHINGABULA, H. M. 1997. Problems of sedimentation in small dams in Zambia. *IAHS Publication,* 245**,** 251-259.

SICHINGABULA, H. M., CHISOLA, M., NYAMBE, I., PHIRI, W., KABIKA, J., MUCHANGA, M., CHOMBA, I., SIKAZWE, H. & CHINONGE, M. Water Resources Management in Kaleya River Basin and Beyond. Consultative Stakeholders' Workshop on Water Resources Management, 2015 Held from 10-11th November, 2015 at Muko Lodge, Mazabuka Town, Zambia.

SICHINGABULA, H. M., NYIRENDA, E., BANDA, K. E. & LEHNER, B. 2020. Hydro-environmental documentation of selected candidate sites for gazetting of Water Resource Protection Areas (WRPAs) in Zambia. Lusaka: Report prepared for WWF-Zambia.

SICHINGABULA, H. M., WALLING, D. E. & COLLINS, A. L. 2000a. Dynamics of Erosion, Sediment Transport and Sediment in Small Catchments. Proceedings of the International workshop on Dynamics, Erosion, Sediment Transport and Sedimentation in Small Catchments, River Motel, Kafue, Zambia, 5-6th July 2000. *Zambia Education Publishing House, Lusaka***,** 165.

SICHINGABULA, H. M., WALLING, D. E. & COLLINS, A. L. 2000b. Measuring suspended sediment fluxes and yields from river basins. In Dynamics of Erosion, Sediment Transport and Sediment in Small Catchments. Proceedings of the International workshop on Dynamics, Erosion, Sediment Transport and Sedimentation in Small Catchments, River Motel, Kafue, Zambia, 5-6th July 2000. *Zambia Education Publishing House, Lusaka***,** 165.

SIMPSON, H. & HERCZEG, A. 1991. Stable isotopes as an indicator of evaporation in the River Murray, Australia. *Water Resources Research,* 27**,** 1925-1935.

SKLASH, M., FARVOLDEN, R. & FRITZ, P. 1976. A conceptual model of watershed response to rainfall, developed through the use of oxygen-18 as a natural tracer. *Canadian Journal of Earth Sciences,* 13**,** 271-283.

SKLASH, M. G. & FARVOLDEN, R. N. 1979. The role of groundwater in storm runoff. *Journal of Hydrology,* 43**,** 45-65.

SMITH, D., MATTHEWS, J., BHARATI, L., BORGOMEO, E., MCCARTNEY, M., MAURONER, A., NICOL, A., RODRIGUEZ, D., SADOFF, C. & SUHARDIMAN, D. 2019. Adaptation's thirst: Accelerating the convergence of water and climate action. *Background paper prepared for the 2019 report of the Global Commission on Adaptation***,** Rotterdam and Washington, DC. Available online at www.gca.org. Accessed on 04/05/21.

SMITH, D. M. & BARCHIESI, S. 2009. Environment as infrastructure: Resilience to climate change impacts on water through investments in nature, led by consortium of CPWC. *IWA, IUCN and WWC, International Union for Conservation of Nature (IUCN).* Gland, Switzerland: International Union for Conservation of Nature (IUCN).

SNADDON, C. D. 1998. *Some of the ecological effects of a small inter-basin water transfer on the receiving reaches of the upper Berg River, Western Cape.* MSc Thesis, University of Cape Town.

STERN, R., RIJKS, D., DALE, I. & KNOCK, J. 2006. INSTAT climatic guide. Reading (UK): University of Reading.

SYAMPUNGANI, S. 2009. *Vegetation change analysis and ecological recovery of the Copperbelt Miombo woodland of Zambia.* Doctoral dissertation, Stellenbosch: University of Stellenbosch.

SYAMPUNGANI, S., GELDENHUYS, C. J. & CHIRWA, P. W. 2011. Miombo woodland utilization and management, and impact perception among stakeholders in Zambia: A call for policy change in Southern Africa. *Journal of Natural Resources Policy Research,* 3**,** 163-181.

TAYE, M. T., WILLEMS, P. & BLOCK, P. 2015. Implications of climate change on hydrological extremes in the Blue Nile basin: A review. *Journal of Hydrology: Regional Studies,* 4**,** 280-293.

TENA, T. M., MWAANGA, P. & NGUVULU, A. 2019. Hydrological Modelling and Water Resources Assessment of Chongwe River Catchment using WEAP Model. *Water,* 11**,** 839.

THEIL, H. 1950. A rank-invariant method of linear and polynomial regression analysis, 1-2; confidence regions for the parameters of linear regression equations in two, three and more variables. *Stichting Mathematisch Centrum. Statistische Afdeling,* (SP 5/49/R).

THERON, S. N., WEEPENER, H. L., LE ROUX, J. J. & ENGELBRECHT, C. J. 2021. Modelling potential climate change impacts on sediment yield in the Tsitsa River catchment, South Africa. *Water SA,* 47**,** 67-75.

TRANG, N. T. T., SHRESTHA, S., SHRESTHA, M., DATTA, A. & KAWASAKI, A. 2017. Evaluating the impacts of climate and land-use change on the hydrology and nutrient yield in a transboundary river basin: A case study in the 3S River Basin (Sekong, Sesan, and Srepok). *Science of the Total Environment,* 576**,** 586-598.

TRAP, J., HÄTTENSCHWILER, S., GATTIN, I. & AUBERT, M. 2013. Forest ageing: an unexpected driver of beech leaf litter quality variability in European forests with strong consequences on soil processes. *Forest ecology and management,* 302**,** 338-345.

TUPPAD, P., KANNAN, N., SRINIVASAN, R., ROSSI, C. G. & ARNOLD, J. G. 2010. Simulation of agricultural management alternatives for watershed protection. *Water Resources Management,* 24**,** 3115-3144.

TUPPAD, P. & SRINIVASAN, R. 2008. Bosque River environmental infrastructure improvement plan: Phase II BMP modeling report. Texas Water Resources Institute. Available electronically from https : / /hdl .handle .net /1969 .1 /86107. Accessed on 23/05/21.

UHLENBROOK, S., FREY, M., LEIBUNDGUT, C. & MALOSZEWSKI, P. 2002. Hydrograph separations in a mesoscale mountainous basin at event and seasonal timescales. *Water Resources Research,* 38**,** 31-1-31-14.

UHLENBROOK, S., ROSER, S. & TILCH, N. 2004. Hydrological process representation at the meso-scale: the potential of a distributed, conceptual catchment model. *Journal of Hydrology,* 291**,** 278-296.

UHLENDAHL, T., SALIAN, P., CASAROTTO, C. & DOETSCH, J. 2011. Good water governance and IWRM in Zambia: challenges and chances. *Water policy,* 13**,** 845-862.

UNFCCC, U. N. F. C. O. C. C.-. 2007. Impacts, vulnerabilities and adaptation in developing countries. United Nations Climate Change Secretariat Bonn, Germany. https://www.climatelearningplatform.org/climate-change-impacts-vulnerabilities-and-adaptation%E2%80%A8-developing-countries. Accessed on 21/05/21.

VALLET-COULOMB, C., SÉRAPHIN, P., GONÇALVÈS, J., RADAKOVITCH, O., COGNARD-PLANCQ, A.-L., CRESPY, A., BABIC, M. & CHARRON, F. 2017. Irrigation return flows in a mediterranean aquifer inferred from combined chloride and stable isotopes mass balances. *Applied Geochemistry,* 86**,** 92-104.

VAN DER LAAN, M., ECKERT, S., DA SILVA, M. & ANNANDALE, J. 2021. A water footprint approach to guide water resource management in data-scarce regions: A case study for the Upper Ewaso Ng'iro Basin, Mount Kenya. *Water SA,* 47**,** 356-366.

VAN LIEW, M. W., FENG, S. & PATHAK, T. B. 2012. Climate change impacts on streamflow, water quality, and best management practices for the Shell and Logan Creek Watersheds in Nebraska, USA. *International Journal of Agricultural and Biological Engineering,* 5**,** 13-34.

WALLING, D., COLLINS, A., SICHINGABULA, H. & LEEKS, G. 2001. Integrated assessment of catchment suspended sediment budgets: A Zambian example. *Land Degradation and Development,* 12**,** 387-415.

WANG, L., WANG, S., ZHOU, Y., ZHU, J., ZHANG, J., HOU, Y. & LIU, W. 2020. Landscape pattern variation, protection measures, and land use/land cover changes in drinking water source protection areas: A case study in Danjiangkou Reservoir, China. *Global Ecology and Conservation,* 21**,** e00827.

WATHUM, G., SEEBAUER, M. & CARODENUTO, S. 2016. Drivers of deforestation and forest degradation in Eastern Province, Zambia. Zambia Integrated Forested Landscape Program. Lusaka: Government Republic of Zambia, Ministry of National Development Planning.

WENNINGER, J., UHLENBROOK, S., LORENTZ, S. & LEIBUNDGUT, C. 2008. Identification of runoff generation processes using combined hydrometric, tracer and geophysical methods in a headwater catchment in South Africa/Identification des processus de formation du débit en combinat la méthodes hydrométrique, traceur et géophysiques dans un bassin versant sud-africain. *Hydrological Sciences Journal,* 53**,** 65-80.

WILLIAMS, J. & GRAFTON, R. Q. 2019. Missing in action: possible effects of water recovery on stream and river flows in the Murray–Darling Basin, Australia. *Australasian Journal of Water Resources,* 23**,** 78-87.

WOLDESENBET, T. A., ELAGIB, N. A., RIBBE, L. & HEINRICH, J. 2017. Hydrological responses to land use/cover changes in the source region of the Upper Blue Nile Basin, Ethiopia. *Science of The Total Environment,* 575**,** 724-741.

WWF 2018a. Integrated Flow Assessment for the Kafue River. Phase 1:Water Resources Developments. WWF Zambia, Lusaka, Zambia.

WWF 2018b. Water Situational Analysis of the Lower Kafue Basin. Socio-Economic Development and Climate Change: Risks and Opportunities. WWF Zambia, Lusaka, Zambia.**,** 1-41.

YAMBA, F. D., WALIMWIPI, H., JAIN, S., ZHOU, P., CUAMBA, B. & MZEZEWA, C. 2011. Climate change/variability implications on hydroelectricity generation in the Zambezi River Basin. *Mitigation and Adaptation Strategies for Global Change,* 16**,** 617-628.

YU, D., LI, X., CAO, Q., HAO, R. & QIAO, J. 2020. Impacts of climate variability and landscape pattern change on evapotranspiration in a grassland landscape mosaic. *Hydrological Processes,* 34**,** 1035-1051.

ZALEWSKI, M., JANAUER, G. A. & JOLÁNKAI, G. 1997. *Ecohydrology: a new paradigm for the sustainable use of aquatic resources,* Paris, UNESCO.

ZHANG, H., WANG, B., LI LIU, D., ZHANG, M., LESLIE, L. M. & YU, Q. 2020. Using an improved SWAT model to simulate hydrological responses to land use change: A case study of a catchment in tropical Australia. *Journal of Hydrology,* 585**,** 124822.

ZHENG, Y., ZHANG, G., WU, Y., XU, Y. J. & DAI, C. 2019. Dam effects on downstream riparian wetlands: the Nenjiang River, Northeast China. *Water,* 11**,** 2038.

ZHOU, W., WANG, J. & CADENASSO, M. L. 2017. Effects of the spatial configuration of trees on urban heat mitigation: A comparative study. *Remote Sensing of Environment*, 195**,** 1-12.

ZHU, T. & RINGLER, C. 2012. Climate change impacts on water availability and use in the Limpopo River Basin. *Water,* 4**,** 63-84.

ZONG, M., HU, Y., LIU, M., LI, C., WANG, C. & PING, X. 2020. Effects of Landscape Pattern Change on Water Yield and Nonpoint Source Pollution in the Hun-Taizi River Watershed, China. *International Journal of Environmental Research and Public Health,* 17**,** 3060.

Appendices

Appendix 4-1: Tracer concentrations of end members and streamflow in the rainy season

Variable	End member	Number	Mean	Standard deviation	Minimum	Maximum
$\delta\,^{2}H$ (‰)	Spring	3	-49.6	0.5	-50.1	-49.3
	Stormwater runoff from irrigated areas	4	-82.7	20.5	-100.2	-54.0
	Stormwater runoff from non-irrigated areas	8	-85.4	4.4	-91.0	-79.0
	Streamflow (not an end member)	9	-70.8	18.1	-99.9	-40.6
$\delta\,^{18}O$ (‰)	Spring	3	-7.5	0.1	-7.6	-7.5
	Stormwater runoff from irrigated areas	4	-11.3	2.7	-13.6	-7.4
	Stormwater runoff from non-irrigated areas	8	-12.3	0.6	-12.9	-11.1
	Streamflow (not an end member)	9	-10.3	2.5	-14.5	-5.9
Electrical conductivity ($mS\ m^{-1}$)	Spring	3	60.3	0.6	59.6	60.7
	Stormwater runoff from irrigated areas	4	98.7	72.8	27.9	182.2
	Stormwater runoff from non-irrigated areas	8	6.5	6.2	0.7	17.1
	Streamflow (not an end member)	9	44.1	19.1	15.5	70.7
Chlorides (mg/l)	Spring	3	12.3	1.2	11.0	13.0
	Stormwater runoff from irrigated areas	4	105.8	91.4	20.0	206.0
	Stormwater runoff from non-irrigated areas	8	9.5	8.6	1.0	20.0
	Streamflow (not an end member)	9	22.3	15.3	12.0	59.0

Appendix 4-2: Tracer concentrations of end members and streamflow in the dry season upstream

Variable	End member	Total	Mean	Standard deviation	Minimum	Maximum
δ ^{2}H (‰)	Irrigation Return flows (upstream via subsurface)	3	-24.9	8.5	-34.1	-17.5
	Spring	2	-48.7	0.9	-49.4	-48.1
	Streamflow upstream (not an end member)	4	-31.4	10.6	-42.6	-18.6
δ ^{18}O (‰)	Irrigation Return flows (upstream via subsurface)	3	-3.0	1.6	-4.7	-1.6
	Spring	2	-7.4	0.4	-7.7	-7.1
	Streamflow upstream (not an end member)	4	-4.0	1.9	-5.7	-1.5
Electrical conductivity (mS m^{-1})	Irrigation Return flows (upstream via subsurface)	3	130.6	32.1	93.6	151.1
	Spring	2	46.1	16.9	34.1	58.0
	Streamflow upstream (not an end member)	4	68.8	26.9	31.1	92.0
Chlorides (mg/l)	Irrigation Return flows (upstream via subsurface)	3	54.7	60.3	14.0	124.0
	Spring	2	52.0	39.6	24.0	80.0
	Streamflow upstream (not an end member)	4	52.0	17.4	36.0	68.0

Appendix 4-3: Tracer concentrations of end members and streamflow in dry season downstream

Variable	End member	Total	Mean	Standard deviation	Minimum	Median
δ ^{2}H (‰)	Irrigation Return flows_downstream	5	-18.6	1.5	-20.2	-18.7
	Wastewater (vinasse)	2	-17.6	1.9	-19.0	-17.6
	Streamflow downstream (not an end member)	3	-17.8	0.9	-18.7	-17.8
δ ^{18}O (‰)	Irrigation Return flows_downstream	5	-2.4	0.5	-2.8	-2.6
	Wastewater (vinasse)	2	-1.3	0.4	-1.6	-1.3
	Streamflow downstream (not an end member)	3	-2.2	0.4	-2.6	-2.2
Electrical conductivity (mS m^{-1})	Irrigation Return flows_downstream	5	76.1	33.4	46.1	78.6
	Wastewater (vinasse)	2	2.3	1.5	1.2	2.3
	Streamflow downstream (not an end member)	3	56.4	4.6	51.1	58.7
Chlorides (mg/l)	Irrigation Return flows_downstream	5	69.2	62.7	32.0	38.0
	Wastewater (vinasse)	2	88.0	14.1	78.0	88.0
	Streamflow downstream (not an end member)	3	76.3	6.8	71.0	74.0

Appendix 4-4: Tracer concentrations of all potential end members with respect to δ ^{2}H

Variable	End member	n	Mean	Standard deviation	Minimum	Maximum
	Groundwater downstream in irrigated area	6	-28.93	6.65	-38.16	-24.35
	Groundwater downstream in non-irrigated area	2	-40.32	8.78	-46.53	-34.1
	Groundwater upstream	2	-50.777	0.152	-50.884	-50.669
	Groundwater downstream _irrigated areas	4	-33.6	10.62	-46.67	-24.64
	Groundwater upstream	4	-49.927	1.712	-51.887	-48.011
	Intra-basin transfer water (irrigation water)	2	-19.738	0.46	-20.063	-19.413
	Irrigation Return flows (upstream via subsurface)	3	-24.9	8.46	-34.1	-17.46
	Irrigation Return flows downstream	5	-18.626	1.461	-20.162	-16.29
	Spring	5	-49.267	0.74	-50.143	-48.092
δ ^{2}H (‰)	Stormwater runoff from irrigated areas	4	-82.7	20.5	-100.2	-54
	Stormwater runoff from non-irrigated areas	8	-85.41	4.36	-91	-78.96
	Streamflow (not an end member)	9	-70.84	18.1	-99.89	-40.6
	Streamflow downstream (not an end member)	3	-17.791	0.925	-18.695	-16.846
	Streamflow upstream (not an end member)	4	-31.36	10.6	-42.64	-18.61
	Subsurface Irrigation Return flows downstream	1	-23.391	*	-23.391	-23.391
	Wastewater	2	-17.63	1.9	-18.97	-16.29
	Wells (Baseflow downstream)	2	-36.9	16.5	-48.6	-25.3
	Wells (Baseflow upstream)	1	-47.354	*	-47.354	-47.354
	Wells (Baseflow)	5	-48.71	7.89	-61.64	-40.54

Appendix 4-4: Tracer concentrations with respect to δ ^{18}O and electrical conductivity

Variable	End member	n	Mean	Standard deviation	Minimum	Maximum
δ ^{18}O (‰)	Groundwater downstream in irrigated area	6	-4.077	1.028	-5.46	-3.365
	Groundwater downstream in non-irrigated area	2	-5.81	1.46	-6.84	-4.77
	Groundwater upstream	2	-7.672	0.183	-7.801	-7.543
	Groundwater downstream _irrigated areas	4	-4.774	1.826	-7.153	-3.238
	Groundwater upstream	4	-7.473	0.288	-7.815	-7.11
	Intra-basin transfer water (irrigation water)	2	-2.4269	0.0246	-2.4443	-2.4095
	Irrigation Return flows (upstream via subsurface)	3	-3.047	1.56	-4.72	-1.632
	Irrigation Return flows downstream	5	-2.397	0.488	-2.758	-1.555
	Spring	5	-7.482	0.236	-7.725	-7.106
	Stormwater runoff from irrigated areas	4	-11.33	2.74	-13.55	-7.41
	Stormwater runoff from non-irrigated areas	8	-12.282	0.619	-12.9	-11.145
	Streamflow (not an end member)	9	-10.27	2.492	-14.483	-5.907
	Streamflow downstream (not an end member)	3	-2.182	0.403	-2.567	-1.764
	Streamflow upstream (not an end member)	4	-4.008	1.891	-5.727	-1.494
	Subsurface Irrigation Return flows downstream	1	-3.0277	*	-3.0277	-3.0277
	Wastewater	2	-1.305	0.353	-1.555	-1.056
	Wells (Baseflow downstream)	2	-5.32	3.06	-7.48	-3.16
	Wells (Baseflow upstream)	1	-7.4568	*	-7.4568	-7.4568
	Wells (Baseflow)	5	-6.939	1.422	-9.137	-5.628

Variable	End member	n	Mean	Standard deviation	Minimum	Maximum
Electrical conductivity (mS m^{-1})	Groundwater downstream in irrigated area	6	844.7	159.8	731	1090
	Groundwater downstream in non-irrigated area	2	776.5	37.5	750	803
	Groundwater upstream	2	658.5	87	597	720
	Groundwater downstream _irrigated areas	4	829	175.7	668	1079
	Groundwater upstream	4	672.8	138.6	525	825
	Intra-basin transfer water (irrigation water)	2	284.5	24.7	267	302
	Irrigation Return flows (upstream via subsurface)	3	1306	321	936	1511
	Irrigation Return flows downstream	5	761	334	461	1278
	Spring	5	546.2	115.2	341	607
	Stormwater runoff from irrigated areas	4	98.7	72.8	27.9	182.2
	Stormwater runoff from non-irrigated areas	8	6.5	6.2	0.7	17.1
	Streamflow (not an end member)	9	44.1	19.1	15.5	70.7
	Streamflow downstream (not an end member)	3	56.4	4.6	51.1	59.5
	Streamflow upstream (not an end member)	4	68.8	26.9	31.1	92.0
	Subsurface Irrigation Return flows downstream	1	144.8	*	144.8	144.8
	Wastewater	2	2.3	1.5	1.2	3.3
	Wells (Baseflow downstream)	2	80.2	19.4	66.4	93.9
	Wells (Baseflow upstream)	1	40.9	*	40.9	40.9
	Wells (Baseflow)	5	97.7	44.7	34.4	148.9

Appendix 5-1: Landcover changes in the upper Kaleya Catchment

Landcover	1984 landcover		2019 landcover		Reforestation NbS landcover	
	Area (km2)	Area (%)	Area (km2)	Area (%)	Area (km2)	Area (%)
Cropland	24.88	31.88	58.69	75.20	35.70	45.75
Forest	40.46	51.84	1.87	2.40	29.05	37.22
Scrubland	12.63	16.18	16.49	21.13	12.04	15.43
Water	0.08	0.10	1.00	1.28	1.25	1.60
Totals	78.05	100.00	78.05	100.00	78.05	100.00

Appendix 5-2: Effects of climate on blue water flow (streamflow) in millimetres (mm)

		MICROC 5					MPI_ISM_LR					Ensemble				
		Historical	RCP 4.5	RCP 4.5 change	RCP 8.5	RCP 8.5 change	Historical	RCP 4.5	RCP 4.5 change	RCP 8.5	RCP 8.5 change	Historical	RCP 4.5	RCP 4.5 change	RCP 8.5	RCP 8.5 change
		m^3 day $^{-1}$	m^3 day $^{-1}$	m^3 day $^{-1}$	m^3 day $^{-1}$	m^3 day $^{-1}$	m^3 day $^{-1}$	m^3 day $^{-1}$	m^3 day $^{-1}$	m^3 day $^{-1}$	m^3 day $^{-1}$	m^3 day $^{-1}$	m^3 day $^{-1}$	m^3 day $^{-1}$	m^3 day $^{-1}$	m^3 day $^{-1}$
Dry season	lower	11201	11310	109	12044	844	9459	12663	3204	12864	3404	12948	15165	2218	17408	4460
	Upper	20914	21000	86	20999	85	17727	22785	5057	23179	5451	19904	22991	3087	25982	6078
	Median	15770	15738	-32	16593	823	13270	17431	4161	17678	4408	16506	19107	2602	21817	5311
Rainy season	lower	33566	32573	-992	38177	4611	28659	43289	14629	43496	14836	20021	25746	5725	32359	12338
	Upper	51520	50132	-1388	57943	6423	44894	62768	17874	63023	18129	33347	40888	7542	49616	16270
	Median	41278	40159	-1119	46734	5456	35494	51612	16118	51980	16486	25581	32024	6443	39620	14039
Annual average	lower	22383	21942	-442	27289	4905	19059	27976	8916	28180	9120	16484	20456	3971	24884	8399
	Upper	36218	35599	-618	42550	6332	31311	42776	11466	43101	11790	26626	31940	5314	37799	11174
	Median	28508	27964	-544	34175	5668	24382	34521	10139	34829	10447	21043	25566	4523	30718	9675

Appendix 5-3 Effects of climate change on sediment load (tonnes)

		MICROC 5					MPI_ISM_LR					Ensemble				
		Historical tons $year^{-1}$	RCP 4.5 tons $year^{-1}$	RCP 4.5 change tons $year^{-1}$	RCP 8.5 tons $year^{-1}$	RCP 8.5 change tons $year^{-1}$	Historical Tons $year^{-1}$	RCP 4.5 tons $year^{-1}$	RCP 4.5 change tons $year^{-1}$	RCP 8.5 tons $year^{-1}$	RCP 8.5 change tons $year^{-1}$	Historical tons $year^{-1}$	RCP 4.5 tons $year^{-1}$	RCP 4.5 change tons $year^{-1}$	RCP 8.5 tons $year^{-1}$	RCP 8.5 change tons $year^{-1}$
Dry season	lower	410	457	47	226	-184	293	480	187	509	216	89	122	33	177	89
	Upper	1788	1768	-20	1549	-239	1355	1891	536	1954	599	1462	1744	282	2116	654
	Median	1217	1230	13	1158	-59	919	1311	392	1350	431	826	1097	271	1427	601
Rainy season	lower	2440	2148	-292	2875	435	1993	3346	1353	3289	1296	578	810	232	1158	580
	Upper	5347	4900	-448	5931	584	4720	6403	1683	6492	1772	3285	4079	793	5001	1715
	Median	4098	3765	-332	4580	482	3537	5079	1542	5116	1579	2214	2937	723	3788	1574
Annual	lower	2850	2605	-245	3101	251	2286	3826	1540	3798	1512	667	932	265	1335	668
	Upper	7135	6667	-468	7480	345	6075	8294	2219	8446	2371	4747	5822	1075	7117	2370
	Median	5315	4995	-320	5738	424	4456	6391	1934	6466	2010	3040	4034	994	5215	2175

Appendix 5-4: Effects of climate change on green water flow (Evapotranspiration) in millimetres (mm)

		MICROC 5					MPI_ISM_LR					Ensemble				
		Historical	RCP 4.5	RCP 4.5 change	RCP 8.5	RCP 8.5 change	Historical	RCP 4.5	RCP 4.5 change	RCP 8.5	RCP 8.5 change	Historical	RCP 4.5	RCP 4.5 change	RCP 8.5	RCP 8.5 change
		mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
Dry season	lower	185	181	-4	128	-57	201	208	6	205	3	202	204	2	203	1
	Upper	199	197	-2	140	-59	217	227	10	222	5	217	223	6	219	2
	Median	192	190	-3	134	-58	210	219	9	214	5	210	214	4	211	2
Rainy season	lower	275	275	0	297	22	291	288	-3	286	-5	299	301	2	296	-4
	Upper	321	324	3	346	25	338	342	3	342	3	344	349	6	346	3
	Median	301	303	2	325	24	318	319	1	318	0	325	329	5	325	0
Annual	lower	459	455	-4	424	-35	492	496	4	490	-1	502	505	4	499	-3
	Upper	520	521	1	486	-34	555	569	14	564	9	560	572	12	565	5
	Median	493	493	0	459	-34	528	538	10	532	5	534	543	9	536	2

Appendix 6-1: Effects of Nature based Solutions on green and blue water, and sediment load under various climate change scenarios

Climate change scenario	Water balance	Water type	Baseline	Recharge structures	Reforestation	Conservation tillage	Combination of all NbSs
			mm	mm	mm	mm	mm
Historical (average rainfall, 709 mm)	Surface runoff	Blue water	19	18	5	18	17
	Baseflow (Groundwater contribution to streamflow)	Blue water	90	92	99	89	107
	Shallow aquifer storage	Blue water	529	529	389	529	531
	Deep aquifer recharge	Blue water flow	17	18	24	17	23
	Initial Soil moisture	Green water storage	131	131	129	132	132
	Change in soil moisture	Green water storage	35	35	34	34	32
	REVAP (Water from shallow aquifer to plants/soil)	Green water flow	5	5	17	5	6
	Evapotranspiration	Green water flow	585	585	599	587	589
	Sediment load (tons year $^{-1}$)		1302	844	1105	1249	676
RCP 4.5 (average rainfall, 749 mm)	Surface runoff	Blue water	29	28	9	29	28
	Baseflow (Groundwater contribution to streamflow)	Blue water	116	120	113	115	118
	Shallow aquifer storage	Blue water	532	531	403	532	541
	Deep aquifer recharge	Blue water flow	22	23	27	22	26
	Initial Soil moisture	Green water storage	139	139	129	139	140
	Change in soil moisture	Green water storage	41	41	35	40	37
	REVAP (Water from shallow aquifer to plants/soil)	Green water flow	9	9	20	9	10
	Evapotranspiration	Green water flow	588	588	606	590	592
	Sediment load (tons year $^{-1}$)		1832	1391	1712	1804	1211
RCP 8.5 (average rainfall, 788 mm)	Surface runoff	Blue water	40	39	15	40	38
	Baseflow (Groundwater contribution to streamflow)	Blue water	139	145	142	138	143
	Shallow aquifer storage	Blue water	528	527	401	528	537
	Deep aquifer recharge	Blue water flow	27	28	34	27	31
	Initial Soil moisture	Green water storage	136	136	127	136	137
	Change in soil moisture	Green water storage	47	47	42	47	44
	REVAP (Water from shallow aquifer to plants/soil)	Green water flow	9	9	20	9	10
	Evapotranspiration	Green water flow	592	592	609	594	596
	Sediment load (tons year $^{-1}$)		2473	2095	2318	2459	1861