

**IMPACTS OF FUTURE CLIMATE AND LANDUSE CHANGES ON
SURFACE-GROUNDWATER BALANCE IN USANGU CATCHMENT**

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**A Dissertation Submitted in Partial Fulfilment of the Requirements for the Degree of
Doctor of Philosophy in Environmental Science and Engineering of the Nelson Mandela
African Institution of Science and Technology**

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ABSTRACT

This study was undertaken to assess the impacts of future climate and land use/cover changes on surface-subsurface water balance in Usangu catchment, located in the Southern highlands of Tanzania. The objectives of the study were achieved through i) use of stable isotopic compositions of water ($\delta^{18}\text{O}$ and $\delta^2\text{H}$), determination of major dissolved ions (K^+ , Na^+ , Mg^{2+} , Ca^{2+} , Cl^- , CO_3^{2-} , SO_4^{2-}) and dissolved silica (SiO_2) for rainfall, rivers, springs and wells to assess the origin, flow pathways and hydrological interconnections of water sources, ii) use of Markov Chain and Cellular Automata models to predict land use/cover change of the whole catchment, iii) use of a simple delta change downscaling method to generate 2010-2039 climate scenario from the General Circulation Models (GCMs), iv) use of Soil and Water Assessment Tool (SWAT) to assess future impacts of land use/cover and climate changes on surface and subsurface water balance, taking Ndembera River watershed as case study, and v) evaluate the effectiveness of water and land management practices as the remedies for the adverse impacts of future land use/cover and climate changes on water resources. The isotopes compositions of water for rivers, wells and springs indicated a recharge by recent meteoric water. Usangu catchment has two flow pathways; a short springs-rivers flow system with low concentrations of dissolved ions, and a slow deeper-aquifer flow pathway which is disconnected from rivers and springs. The changes in land use/cover affected water resources negatively. At the whole Usangu catchment scale, from 2013 to 2020, the urban and agricultural lands were predicted to increase by 8.2% and 1%, respectively, while forestlands would decrease by 20.6%. For Ndembera River watershed alone, the area under agriculture and evergreen forest would increase by ~10% and 7%, respectively. Also, forestland would decrease by ~12%, and in turn, would decrease the total water yield by ~13%, while the evapotranspiration and overland runoff would increase by ~8% and ~18%, respectively. The period 2010-2039 was shown to be warmer (1.1°C) and wetter (about 2-7% in the wet months) than the baseline period (1980-2009), exacerbating the adverse impacts of land use/cover change. Water stress in the catchment caused by future climate and land use/cover changes could be reduced by management practices such as filter strips, grassed waterways and terracing and contouring.

DECLARATION

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

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The above declaration is confirmed

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CERTIFICATION

The undersigned certify that have read and hereby accept the dissertation titled “*Impacts of future climate and landuse changes on surface-groundwater balance in Usangu catchment*”, in fulfilment of the requirements for the Degree of Doctor of Philosophy in Environmental Science and Engineering (EnSE) at the Nelson Mandela African Institution of Science and Technology (NM-AIST)

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DEDICATION

This research work is dedicated to Environmental Science modellers and my family.

TABLE OF CONTENTS

ABSTRACT.....	i
DECLARATION	ii
COPYRIGHT.....	iii
CERTIFICATION	iv
ACKNOWLEDGEMENT	v
DEDICATION.....	vii
LIST OF TABLES	xii
LIST OF FIGURES	xiii
LIST OF APPENDICES	xvii
LIST OF ABBREVIATIONS AND SYMBOLS	xviii
CHAPTER ONE	1
INTRODUCTION	1
1.1 Background Information.....	1
1.2 Problem statement and justification of the study.....	7
1.2.1 Statement of the Problem	7
1.2.2 Significance of the research	8
1.2.3 Research Objectives	9
1.2.4 Research questions	9
1.3 Structure of the dissertation	12
CHAPTER TWO	13
Characterization of surface-groundwater hydrological processes in Usangu catchment: Isotopic and hydrochemistry perspective.....	13
Abstract	13
2.1 Introduction.....	14
2.2 Material and methods.....	15
2.2.1 Study area description	15
2.2.2 Fieldwork.....	17
2.2.3 Laboratory Analysis	18
2.2.4 Data Quality Assessment.....	20
2.2.5 Data Analysis	20

2.3 Results.....	21
2.3.1 Physical parameters (TDS, pH and EC) and SiO ₂ constituents in water sources	21
2.3.2 Major dissolved cations.....	22
2.3.3 Major dissolved anions.....	23
2.3.4 Stable isotopes of water ($\delta^{18}\text{O}$ and δD).....	24
2.3.5 Source and seasonal variations of water chemical and physical parameters	25
2.3.6 Variations of $\delta^{18}\text{O}$ and δD composition in water sources	27
2.3.7 Rock-water interactions and hydrochemical facies.....	32
2.3.8 Factor analysis results	35
2.3.9 Hierarchical cluster analysis of water sources	36
2.4. Discussion.....	39
2.4.1 Surface-groundwater interaction	39
2.4.2 Predominant facies and origin of groundwater	44
2.4.3 δD and $\delta^{18}\text{O}$ variations in relation to surface-groundwater interconnection.....	45
2.4.4 Hydrological connections and flow pathways.....	47
2.4.5 Factors influencing variations in $\delta^{18}\text{O}$ and δD concentrations in rainwaters	51
2.5. Conclusions.....	54
CHAPTER THREE	56
A Markovian and cellular automata land-use change predictive model of the Usangu Catchment	56
Abstract.....	56
3.1 Introduction.....	57
3.2 Materials and Methods.....	60
3.2.1 Study area	60
3.2.2 Land use/cover data sources and classification.....	61
3.2.3 Landsat imagery processing and land use/cover classification	62
3.2.4 Land Use/Cover Classification Accuracy Assessment	63
3.2.5 Prediction of future land use/cover dynamics	64
3.2.6 Land use/cover change prediction framework	71
3.3 Results.....	72
3.3.1 Land use/Cover Classification Accuracy	72
3.3.2 The probabilities of land use and cover change	72

3.3.3 Model validation results	73
3.3.4 Simulated land use and cover of 2020 and dynamics	75
3.4 Discussions	76
3.4.1 Probabilities of land use and cover change	76
3.4.2 Evaluation of model validation results	77
3.4.3 Future land use/cover and dynamics	80
3.5 Conclusion	82
CHAPTER FOUR.....	84
The impact of future climate and land use/cover change on water resources in the Ndembera watershed and their mitigation strategies.....	84
Abstract	84
4.1 Introduction.....	85
4.2. Material and methods.....	86
4.2.1 Study area	86
4.2.2 The description of SWAT model	87
4.2.3 Preparation of the ArcSWAT model inputs	89
4.2.4 SWAT Model set-up and parameterization.....	94
4.2.5 SWAT model calibration and validation.....	95
4.2.6 SWAT model performance evaluation.....	97
4.2.7 Calibration and validation of future climate data	97
4.2.8 Simulation of the impacts of future land use/cover, climate and land management practices on water balance	101
4.3 Results.....	102
4.3.1 Sensitivity analysis results.....	102
4.3.2 Performance of the SWAT model and Uncertainty Analysis	103
4.3.3 Evaluation of the GCMs-derived climate data	106
4.3.4 Current and future trends of mean climate in the watershed.....	110
4.3.5 Land use/cover change and its impact on the catchment water balance	113
4.3.6 Impact of future climate change on the catchment water balance	115
4.3.7 Impacts of management practices on water balance and river discharge.....	117
4.4 Discussion	119
4.4.1 Model parameterization and sensitivity analysis.....	119

4.4.2 Adequacy of the SWAT model and GCMs-derived data for hydrological processes simulation.....	120
4.4.3 The trend of climate change in the Ndembera watershed	122
4.4.4 The impact of land use/cover change on water balance and river discharge	122
4.4.5 The impact of near-term climate change on water balance and river discharge	124
4.4.6 The impact of land and water management practices as mitigation strategies.....	125
4.5 Conclusion	126
CHAPTER FIVE	128
5.1 General discussion	128
5.2 General conclusion.....	131
5.3 Scientific contribution.....	133
5.4 Recommendations.....	137
REFERENCES	139
APPENDICES	166

LIST OF TABLES

Table 1: The effects of water sources and sampling seasons on hydrochemical parameters .	26
Table 2: Tukey HSD Multiple Comparison results	27
Table 3: Correlation coefficients matrix of water samples of Usangu catchment	34
Table 4: Extracted Components (Factors), Eigenvalues and variance explained	35
Table 5: Water sources and their possible origin in the Usangu catchment	45
Table 6: Characteristics of satellite imageries used	62
Table 7: Land use/cover classes and their descriptions	63
Table 8: Classification accuracy (%) for LULC maps for the year 2000, 2006 and 2013	63
Table 9: Criterion development data sources.....	65
Table 10: Factors, constraints, membership functions and control points used for preparation of suitability maps	68
Table 11: Probability transition matrix for simulation of land use and cover in year 2013 by using land use and cover images of 2000 and 2006	73
Table 12: Results of validation analysis-Agreement/disagreement components	75
Table 13: Land use and cover change matrix for 2013-2020 (km ²)	76
Table 14: Crops growing calendar in Usangu Catchment in a hydrological year	95
Table 15: Parameters sensitive to streamflow, their default range, fitted value during calibration and final values used in SWAT model for streamflow simulations.....	96
Table 16: Selected CMIP5-GCMs for forcing the SWAT model.....	100
Table 17: List of SWAT input parameters and values used for each management practice	102
Table 18: SWAT model's calibration and validation statistical analysis results.....	104
Table 19: Statistical analysis results of the monthly precipitation and temperature for the baseline and verification periods	109
Table 20: Changes in the water balance ratios under 2013 and 2020 land use/cover scenarios	114

LIST OF FIGURES

Figure 1: Summary of data, steps, processes involved in the study and their outcomes	11
Figure 2: Map of Usangu catchment location showing rock types, sampling sites and other physical features (Source: Modified after Robert, 2013).....	16
Figure 3: Locations in Tanzania where $\delta^{18}\text{O}$ and δD data for LMWL fitting were obtained. The fitted LMWL is shown as insertion (top left corner) in Fig. 9.	19
Figure 4: The mean values of TDS (a), pH (b), EC (c) and dissolved Silica (d) in water sources for all seasons. The whiskers show the minimum and maximum values	22
Figure 5: The mean concentrations of major cations in the water sources for all seasons. The whiskers show the minimum and maximum values	23
Figure 6: The mean concentrations of major anions in the water sources for all seasons. The whiskers show the minimum and maximum values	24
Figure 7: The mean concentrations of ^{18}O (a) and ^2H (b) in water sources for all seasons. The whiskers show the minimum and maximum values	25
Figure 8: The $\delta^{18}\text{O}$ and δD composition in water from rain (a and b), springs (c and d), wells (e and f) and rivers (g and h).....	30
Figure 9: A plot of $\delta^2\text{H}$ versus $\delta^{18}\text{O}$ values of water samples along LMWL	31
Figure 10: Piper diagram showing predominant facies for various water sources (Water type regions 1, 2, 3...6 are arranged according to Saravanan et al., 2015)	33
Figure 11: Plot of loadings for Factor 1 and 2 (a), Factor 2 and 3 (b) and Factor 3 and 4 (c)	36
Figure 12: Cluster dendrogram of the samples from the three types of water source	37
Figure 13: The Schoeller diagram to show the concentration of water sources in the three clusters (Source: After Thyne <i>et al.</i> , 2004).....	38
Figure 14: Plot of $\delta^{18}\text{O}$ against δD showing the distribution of end-members of each cluster along the LMWL.....	39
Figure 15: Gibbs diagrams with the samples labeled according to their respective clusters (Source: After Gibbs, 1970).....	40
Figure 16: The ionic ratios (a and b), scatter diagrams of different hydrochemical parameters (c-e) and a plot of SiO_2 vs $\delta^{18}\text{O}$ (f)	42
Figure 17: Conceptual diagram of Usangu catchment major hydrological processes, water sources, and chemical reactions governing hydrochemistry.....	50

Figure 18: Elevation versus mean TDS values in water sources	51
Figure 19: Mean monthly temperature and monthly precipitation trend for Matamba weather station (Data arranged according to Usangu Catchment Hydrological year (Data Source: RBWB, 2014)	53
Figure 20: Daily precipitation records for February and April at Matamba weather station (Circled dates are the sampling dates (Data Source: RBWB, 2014)	53
Figure 21: Deuterium excess values of rainwaters in Usangu catchment	54
Figure 22: Map of the study area	61
Figure 23: Steps used to prepare land use/cover suitability maps under MCE	66
Figure 24: Land use and cover classes suitability maps for grassland (a), wetlands (b), woodland (c), forestland (d), Shrubs (e), agricultural land (f), barren land (g), water (h), and urban land (i). The “Quant” Palette file in IDRISI Selva is used to display colour of raster images. The colour is scaled from 0-255, except (h) where “0” denotes a restricted area for suitability analysis and “1” represents areas suitable for suitability analysis	70
Figure 25: CA-MARKOV modelling steps to achieve simulated land use and cover of 2020	71
Figure 26: Observed land use and cover of 2013(a) and Simulated land use and cover 2013 (b) (Sources: Fig. 25 (a) adopted from Canute et al., 2015)	74
Figure 27: Simulated land use and cover of 2020 of Usangu Catchment.....	75
Figure 28: Changing quantity and allocation error by changing images resolutions	79
Figure 29: Location of Ndembera watershed showing major farm and irrigation schemes...	87
Figure 30: Water balance components and movement of water in the land phase hydrological cycle during SWAT simulation (Source: After Arnold et al., 2009)	89
Figure 31: DEM of Ndembera River Catchment. The watershed was delineated using the 1ka33 gauging station at the most downstream outlet	90
Figure 32: Slope map of Ndembera River Catchment.....	91
Figure 33: Ndembera River Catchment soil types	91
Figure 34: SWAT Land Use types (2013) of Ndembera River Catchment.....	92
Figure 35: The 2020 land use/cover of Ndembera River Catchment	92

Figure 36: Climate Forecast System Reanalysis rainfall data before and after bias correction	93
Figure 37: Schematic diagram showing the workflow to generate future climate variables in the present study	99
Figure 38: Temperature-and-Precipitation change scatter diagram for Kinyanambo station (83353).....	100
Figure 39: The t-statistic and p-values of the calibrated parameters of Ndembera River watershed	103
Figure 40: Comparison between simulated and observed monthly discharge of Ndembera River (a) and the 95 Percent Prediction Uncertainty band (b).....	105
Figure 41: Observed and GCMs-derived mean monthly precipitation for Kihanga the three weather stations (a=Kihanga, b=Ikweha and c=Kinyanambo) during baseline and verification periods	107
Figure 42: Observed and GCMs-derived mean monthly temperature for the three weather stations (a=Kihanga, b=Ikweha and c=Kinyanambo) during baseline and verification periods	108
Figure 43: Trend of annual mean precipitation amounts from 1980-2009 (a) and 2010-2039 (b).....	110
Figure 44: Mean monthly temperature trend from 1980-2009 (a) and 2010-2039 (b).....	111
Figure 45: Monthly total precipitation of Ndembera watershed averaged over the whole baseline and near-term periods	112
Figure 46: Average monthly maximum (a) and minimum (b) temperature of Ndembera watershed for baseline and near-term periods	112
Figure 47: Land use/cover of the baseline (2013), future (2020) period and their changes .	113
Figure 48: Water balance of Ndembera watershed under 2013 and 2020 land use/cover scenarios.....	114
Figure 49: Ndembera River discharge at 1ka33 under the 2013 and 2020 land use/cover scenarios.....	115
Figure 50: Near-term water balance simulated under the GCMs ensemble mean climate data compared to the baseline water balance.....	116
Figure 51: Mean monthly river discharge of Ndembera River at 1ka33 under the near-term climate scenario compared to the baseline.....	117

Figure 52: Water balance under specific land and water management scenarios compared to the reference water balance scenario derived from near-term climate	118
Figure 53: Hydrographs of Ndembera River at 1ka33 under different land and water management practices compared the reference hydrograph	119

LIST OF APPENDICES

Appendix 1: Names, Coordinates and Codes for each sampling site	166
Appendix 2: Soils and Water Management Practices.....	167

LIST OF ABBREVIATIONS AND SYMBOLS

AHP	Analytic Hierarchy Process
ANOVA	Analysis of Variance
CA-Markov	Cellular Automata and Markov Chain
CFSR	Climate Forecast System Reanalysis
CGIAR	Consultative Group for International Agricultural Research: is a global partnership that unites organizations engaged in research for a food secure future
CMIP5	Coupled Model Intercomparison Project Phase 5
cumecs	Cubic meter per second: A unit measure for river discharge
D	A symbol used in this study to denote a well as a source of groundwater
DA_RCHG	Deep aquifers recharge (mm). The amount of water from the root zone that recharges the deep aquifer during the time step ($DA_RCHG = GW_RCHG - \text{Shallow aquifer recharge}$)
DEM	Digital Elevation Model: a raster-based representation of topography
EC	Electrical Conductivity ($\mu\text{S/m}$)
ET	Actual Evapotranspiration in the watershed during the simulation (mm): the combination of plant transpiration and evaporation of water from soil, surface water, and vegetation surfaces
FAO	Food and Agriculture Organisation of the United Nations
GCM	General Circulation Model
GDP	Gross Domestic Product
GHG	Green House Gases
GIS	Geographic Information System: software tools used in the development and analysis of spatial data
GW_Q	Groundwater contribution to stream flow (mm). Water from the shallow aquifer that enters the main channel during the time step. It is also referred to as base flow
GW_RCHG	Total amount of water entering shallow and deep aquifers during the time step (mm)
GNIP	Global Network for Isotopes Precipitation
HCA	Hierarchical Cluster Analysis

HDPE	High-Density Polyethylene
HSD	Honestly Significant Difference
IAEA	International Atomic Energy Agency
LAT_Q	Lateral flow contribution to stream flow in watershed for the simulation (mm).Water from the soil profile
LMWL	Local Meteoric Water Line
LULC	Land use and land cover: describes the natural and human-made landscapes
MCE	Multi-Criteria Evaluation
MWSWAT	Map Window SWAT
NASA-GISS	National Aeronautics and Space Administration- Goddard Institute for Space Studies
NBS	Tanzania National Bureau of Statistics
NSE	Nash-Sutcliffe Efficiency: a model evaluation quantity
P	A symbol used in this study to denote precipitation water source
PBIAS	Percent bias: a model evaluation quantity
PC	Principal Component
PCA	Principal Component Analysis
PERC	Water that percolates past the root zone during the time step (mm).
PREC	Precipitation: Average amount of precipitation for the day, month or year (mm)
Q	River Flow/Discharge (cumecs)
R	A symbol used to denote a river water source in this study
RBWB	Rufiji Basin Water Board
RCP	Representative Concentration Pathway
REVAP	Water in the shallow aquifer returning to the root zone in response to the moisture deficit during the time step (mmH ₂ O)
S	A symbol used in this study to denote a spring water source
SAGCOT	Southern Agricultural Growth Corridor of Tanzania
SHAL A Q	Shallow aquifer/groundwater contribution to stream in watershed for the simulation (mm)

SMUWC	Sustainable Management of Usangu Wetland and its Catchment
SRTM	Shuttle Radar Topography Mission
SUFI	Sequential Uncertainty Fitting
SUR_Q	Surface runoff generated in the watershed for the simulation (mm), it occurs along a sloping surface (mm)
SWAT	Soil and Water Assessment Tool: a distributed-parameter, landscape-scale, open-source hydrologic model
SWAT-CUP	SWAT Calibration and Uncertainty Program
TANROADS	Tanzania National Roads Agency
TLOS	Transmission losses: Losses of surface flow via leaching through the streambed
URT	United Republic of Tanzania
VSMOW	Vienna Standard Mean Ocean Water
WB	Water Balance
WLC	Weighted Linear Combination
WPR	World Population Review
WYLD	Total water yield (mm). The net amount of water that leaves the sub-basin and contributes to stream flow in the reach during the time step (mm). It is calculated as follows: $WYLD = SURQ + LATQ + GWQ - TLOSS - \text{pond abstractions}$.
WWF	World Wildlife Fund
W/m ²	Watts per meter squared: Unit used for measuring the radiative forcing

CHAPTER ONE

INTRODUCTION

1.1 Background Information

In order to ensure sustainable management and use of surface and groundwater resources, the knowledge on the impacts of factors such as historical and future changes in the land use and climate on water balance of a watershed is indispensable. These factors, together with the understanding of the surface-groundwater flow pathways and interactions, can be very useful in developing some effective land and water management practices as the remedies for the impacts of land use and climate change. It is well established that changes in land use and climate are adversely impacting the watershed hydrology (Andualem and Gebremariam, 2015; Dwarakish and Ganasri, 2015; Zhang *et al.*, 2016). The impacts are expected to increase in the future due to increasing clearance of virgin forest lands for agriculture and elevated global warming (Fischer, 2013). Thus, the way in which future climate will interact with the land use changes and affect the water balance in the watersheds requires more attention.

Changes in land cover (bio-physical attributes of the earth's surface) and land use (human modified earth's surface) has been accelerating as a result of socio-economic and bio-physical drivers (Behera *et al.*, 2012). Such drivers include the expansion of agricultural production through clearance of forest lands, to feed the global growing population (Fischer *et al.*, 2013). The growing population will create a demand for more shelter, fiber and water for various purposes, which in turn, leads to worldwide changes to forests, farmlands and waterways (Foley *et al.*, 2005; Byerlee *et al.*, 2014). These changes cause adverse environmental trends which include the shortages of fresh water; soil degradation; deforestation; and loss of biodiversity (Ezeh *et al.*, 2012). Moreover, they cause alteration of the hydrologic processes in a watershed such as evapotranspiration, infiltration, surface runoff, groundwater flow and stream discharge regime (Bieger *et al.*, 2015; Natkhin *et al.*, 2015). Therefore, the quantification of the spatial-temporal land use changes, both historical and future changes as well as evaluation of their impacts on water balance of a watershed may help to generate information for effective management of water resources.

Usangu plains have experienced changes in land use due to agricultural land use intensification which mainly takes place particularly in areas accessible to irrigation and potential for rice production (Lyimo, 2017). The quantification of land use changes and their implications on the water resources in Usangu plains have been carried out by previous researchers such as Mwalukasa (2002), Kashaigili *et al.* (2006a), Kashaigili *et al.* (2006b), Canisius *et al.* (2011) and Lyimo (2017). All these studies, except Lyimo (2017) and Mwalukasa (2002), covered only the Usangu wetlands, a section of Great Ruaha River catchment and its surrounding areas. Out of those studies carried in the Usangu wetlands, it is only Kashaigili *et al.* (2006a) and Kashaigili *et al.* (2006b) works that linked land use changes to the stream flow changes. Mwalukasa (2002) assessed the relationship between land degradation and land use changes in Chimala River catchment, while Lyimo (2017) studied the impacts of land use change and livelihood diversification in Imalilo village in Mbarali district. In this regard, the land use and cover changes have been carried out only in small portion of the whole Usangu catchment, making the information on land use changes of the whole catchment and its important river watersheds such as Kimani, Ndembera and Kyoga to remain unknown. In addition, there is a missing information about the impact of land cover changes on other hydrological/water balance components rather than streamflow, such as evapotranspiration, groundwater recharge, water yield and runoff. Furthermore, the information about the future land use and cover changes in the watershed is not available. In this study, the cellular automata and Markov models are used to generate the future (2020) land use and cover scenario of the whole Usangu catchment, and simulate its impacts on the water balance of the catchment.

The decline of river flows both into Usangu wetlands and its availability downstream in the Great Ruaha River has been acknowledged by previous researchers such as Kashaigili *et al.* (2006b), Canisius *et al.* (2011) and Sosovele (2007). This decline has been attributed to factors such as expansion of agricultural activities in the valley bottoms known as “vinyungu” (Sosovele, 2007), open up of commercial irrigated rice farms (Sosovele, 2007; Kashaigili, 2008) and population growth (Madulu, 2004; Lyimo, 2017). As a consequence, major land use changes resulted, for example, between 1984-2000 there was a decrease of vegetative swamps cover and closed woodlands in the Usangu wetlands by 67% and 87%, respectively (Kashaigili *et al.*, 2006a). There was also a decline in flow into Usangu wetland

by 70% between 1958-2004, as well as observed decline in outflow to the wetland's downstream (Kashaigili *et al.*, 2006b). Despite the knowledge of these historical changes, the future status of land use cover and its impacts on water resources based on the observed historical population growth and agricultural expansion is unknown. Thus, there is a need to predict the future spatial-temporal land use and cover changes based on the knowledge of land use change drivers, not only in the Usangu wetland, but in the whole Usangu catchment that may help to plan for preventive measures for any foreseeable adverse impacts.

Climate data analysis in Africa shows that temperature increased by 1–2°C between 1970 and 2004; and a similar rise is predicted by the end of 2025 (Mitchell, 2013). It is also predicted that there will be changes in precipitation (both in quantity and in the nature of events). Rainfall events are expected to become less frequent and more severe. These changes will result in a change in surface water availability. Reduced precipitation will impact freshwater ecosystems and water availability for humans. Some previous researchers who conducted studies in East African countries such as Mckenzie *et al.* (2010) and Faramarzi *et al.* (2013) revealed that water resources are facing threat from the projected climate change, and thus there is a need to consider the projected future climate changes in future water resource planning.

In Tanzania, climate change has been linked to a number of hydrological changes in different catchments such as Usangu (Malley, 2011) and Wami-Ruvu (Wambura *et al.*, 2015). According to Malley (2011), climate change is associated to the drying up of Great Ruaha River in the Ruaha National Park every dry season during 1990s and 2000s. Other researchers such as Shu and Villholth (2012) attributed the drying up of Great Ruaha river to the decline in baseflow in the Great Ruaha, Mbarali and Ndembera_rivers from 1960-2009, which was brought about by both climate factors (precipitation and evapotranspiration) and human activities. A recent study by Mbaga (2015) in Mbarali River watershed reported that between 2002-2003 the 12% decrease in precipitation resulted in decline of river runoff volume by about 19.6%. In fact, local people in Usangu catchment are aware of the changing climate and variability, including seasonal forecasts, and they are using various indicators to explain the changing conditions (Kangalawe *et al.*, 2011). What is lacking is the knowledge of long term future climatic scenario of the catchment, which in this study the General

Circulation Models (GCMs) are used to generate the near-term (2010-2039) climatic scenarios.

Land use and climate changes occur simultaneously (Palamuleni *et al.*, 2011). Their combined effects can lead to changes in the availability of water resources required for economic activities such as agricultural production and hydroelectric power generation (McCartney *et al.*, 2007; Rajabu, 2007; Kadigi *et al.*, 2008). Most of climate and land use change studies in relation to water resources in Usangu catchment or in its small River watersheds focused either on climate change alone (Mbagi, 2015) or land use change alone (Sosoovele, 2007). Therefore, there is a need for further study to understand the way in which the present and future climate will interact with the land use change such as agricultural expansion in Usangu catchment and affect the water balance.

Adaptation or remedies to the adverse impacts of climate and land use changes require some land management practices (Malley *et al.*, 2009a). Some of the land and water management practices which have been applied in Usangu catchment include environmental education and afforestation programs (Kashaigili *et al.*, 2009) and growing trees and shrubs (Malley *et al.*, 2009a). The mechanical water management practices, contour bunds and terraces, were once used in the Uporoto Mountains, but for unknown reasons they were abandoned despite their effectiveness in improving soil moisture (Mwanukuzi, 2011). There are also other management practices such as filter strips, contour and terracing and grassed waterways which can improve soil capacity to maintain moisture (Arnold *et al.*, 2013). So far, the effectiveness of management practices in Usangu catchment as adaptation strategy or remedies for the impacts of climate and land use changes on water balance and streamflow have not yet been studied.

Usangu catchment is important for Tanzania food base as it produces about 30% of Tanzanian rice (SMUWC, 2001b; Mbagi, 2015). It is endowed with many large and perennial rivers; Ruaha, Kimani, Mbarali, Ndembera and Chimala Rivers, which flows from the Poroto and Kipengere Mountains, supporting many irrigation schemes in the mid and lowlands. The water in the lowlands supports the life of wildlife in the Ihefu and Ruaha national park (Kashaigili *et al.*, 2006b; Tumbo and Hughes, 2015). Despite its economic and ecological importance of the water resources in the catchment, the origin of water sources,

the flow pathways and hydrological connection of water sources is not adequately understood.

Some considerable advances have been made globally in the understanding of watersheds hydrological process such as the origin of water sources and the flow pathways using stable isotope and dissolved ions as tracers (Taylor and Howard, 1996; Louise, 2009; Mul, 2009; Bushman *et al.*, 2010; Hrachowitz *et al.*, 2011). Despite such advancements, the use of stable isotope and dissolved ions as tracers have received insignificant applications in most of watersheds in the developing countries, such as Usangu catchment in Tanzania and in other East African countries. As a result, most of the watersheds in East African countries continue to suffer from lack of reliable long-term hydrological data which makes it difficult to carry out accurate assessments of available surface and groundwater resources (Mutenyo *et al.*, 2013). This situation limits the formulation of effective water management policies (Howard and Karundu, 1992; Kashaigili, 2010; Mckenzie *et al.*, 2010). Furthermore, the study on assessment of groundwater availability in Tanzania by Kashaigili (2010) showed that the quantification of the groundwater resources of the country has not yet been possible because of a lack of requisite data. In most cases, the only available information has been compiled from existing borehole log data. The hydrogeology data is scattered, fragmented and usually incomplete. Therefore, this study uses the stable isotopes ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) of water and hydrochemistry data (K^+ , Na^+ , Mg^{2+} , Ca^{2+} , Cl^- , CO_3^{2-} , SO_4^{2-} and SiO_2) for rainfall, rivers, springs and wells as tools to generate information to fill the hydrological data gap in Usangu catchment.

Tanzania is one of sub-Saharan Africa countries whose population has increased almost four times from 12.3 million in 1967 to 48.8 million in 2015 (URT, 2016). The current annual population growth rate is 3.0%. If this trends continues, it is projected that Tanzania will have a population of 95.5 million by 2050 (WPR, 2016). This population growth will necessitate the country to increase areas for agricultural production to feed the growing population.

In order for Tanzania to be able to produce enough food to feed the growing population, Usangu catchment which falls within the Southern Agricultural Corridor of Tanzania (SAGCOT) has been identified as one of the areas for food production intensification (Buck

and Milder, 2012). Despite water shortage facing the catchment (Nnunduma, 2005), major agricultural intensification is taking place in this catchment to meet national food security goals, reducing poverty and spurring economic development (Buck and Milder, 2012). The future success of agricultural growth in Usangu catchment will depend on how the country will address the impacts of climate change, destructive land use changes, environmental degradation, the existing water stress (Kashaigili *et al.*, 2006a; Kashaigili, 2008; Buck and Milder, 2012). In this study, effectiveness of land and water management practices as the remedy for the water stress in Usangu catchment due to changes in land uses and climate change are assessed using Soil and Water Assessment Tool (SWAT).

SWAT is one of the hydrological models which have been applied successfully in the Upper Nile basin countries, mostly in the areas located in the Ethiopia highlands and around Lake Victoria; addressing a variety of problems such as erosion, land use and climate change impact and water resources management (Griensven *et al.*, 2012). In Tanzania, SWAT model has been applied in the assessment of water balance in Zanzibar (Haji, 2010), impacts of climate change on runoff of Wami river basin (Wambura *et al.*, 2015), and land use change impacts on Kihansi River hydrology (Birhanu, 2009). The studies related to SWAT model validation and parameterization were carried out by Mulungu and Munishi (2007) in Simiyu River watershed and in Pangani river basin (Ndomba *et al.*, 2005; Ndomba *et al.*, 2008). Among all studies which involved the application of SWAT in Tanzania, only one study by Natkhin *et al.* (2015) in Ngerengere river assessed the combined effects of the impacts of land use and climate changes on discharge regime. Thus, making the combined effects of land use and climate changes of many river watersheds in Tanzania such as those in Usangu catchment not well understood.

Although application of SWAT has been successful in other watersheds in Tanzania, only one study by Elzein (2010) was conducted in Usangu catchment to investigate the suitability of SWAT model for land use change impact assessment on stream flows. In addition, none of the studies in Usangu catchment ever incorporated the projected future land use and cover in the SWAT model for water balance simulations. Therefore, further studies using hydrological model, SWAT, are required so as to generate information on the combined effect of current and future land use and climate changes on water balance for

improved water resources management. The SWAT model has many benefits as it offers the possibility to simulate and evaluate the effectiveness of some land and water management practices such as terracing and contouring, filter strips, grassed waterways and tillage practices as discussed by Arnold *et al.* (2013). Nevertheless, the information on the applicability of these management practices in Usangu catchment is lacking.

This study, therefore, focused on assessing the impacts of future land use and climate change on water balance in Usangu catchment, as well as the evaluation of land and water management practices as antidotes to the adverse impacts climate and land use changes. In this study, the insight of the origin of water, flow paths and surface-groundwater interconnections using stable isotopes and hydrochemistry as well as prediction of future (2020) land use and cover changes using Markov Chain and Cellular Automata models covered the whole Usangu catchment. However, the assessment of the impacts of future land use and climate changes on water balance and river discharge considered only Ndembera River watershed as a case study.

1.2 Problem statement and justification of the study

1.2.1 Statement of the Problem

Usangu catchment is crucial for Tanzania food base as it produces about 30% of Tanzanian rice (Mbaga, 2015). The area has also been identified as a part of Rufiji basin where the intensification of agriculture production is going to take place to enable Tanzania to feed its growing population and boost economic growth (Milder *et al.*, 2012). Water in rivers found in Usangu catchment not only play important role in irrigated rice and other crops in the respective river watersheds, but is also crucial for wildlife in the Ruaha National Park ecosystem and hydroelectric power generation at Mtera dam (Magayane and Mdemu, 2005; Sosovele, 2007). Despite the economic and the ecological importance of the Usangu catchment, the hydrological processes in this catchment such as origin of water sources, their flow pathways and the interconnections of surface and subsurface water are not known.

Furthermore, the catchment is already a water stressed area (Mdemu *et al.*, 2003; Kadigi *et al.*, 2008; Malley *et al.*, 2009b), which makes possibility of agricultural intensification uncertain. Water stress is brought about by some factors such as the increase in water abstraction for irrigation and land use changes such as the decreased woodlands in the

Usangu wetland and surrounding areas from 30% to 23% due to cultivation (Kashaigili *et al.*, 2006a). Water stress is also attributed to climate change (Malley, 2011; Shu and Villholth, 2012; Mbaga, 2015). Climate change scenarios across multiple GCMs show increase in the country's averaged mean temperatures of 1.3°C and 2.2°C projected by 2050 (Noel, 2012). Nevertheless, the degree to which future land use and climate changes will interact and affect surface-groundwater balance of Usangu catchment has not been established.

This study, therefore, assessed the origin, flow pathways and interconnection between surface and sub-surface water using stable isotopes ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) and hydrochemistry of water in order to generate information necessary for effective assessment of water resources and formulation of water resources development plans. In addition, the study assessed the impacts of future land use and climate changes on water balance in Ndembera river watershed and Ndembera river flow using SWAT. It further evaluated the effectiveness of land and water management practices as remedies for the adverse impacts of future land use and climate changes on water balance and river flow.

1.2.2 Significance of the research

The availability of enough quantities of surface and subsurface water to meet economic and environmental demands amid the growing population, expanding irrigated agriculture and climate change is a matter of great concern in Usangu catchment as well as wildlife and hydroelectric power generation to the downstream. The sustainable and efficient utilization of the available water resources in this catchment requires careful planning and management strategies. These plans and strategies must be guided by solid understanding of the hydrological processes in the catchment and the factors that are influencing them such as present and future land use and climate changes. This guarantees the appropriate management of the available water resources. This study, therefore, identified the origin of water in different sources (springs, rivers and wells), their flow pathways and interconnections of surface and subsurface water in Usangu catchment catchment. Furthermore, the future (2020) land use change of the catchment and later assessed the impacts of this future land use and climate change on water balance and streamflow in Ndembera River watershed. In addition, the appropriateness of land and water management

practices to reduce the negative impacts of future land use/cover and climate change were evaluated. The knowledge and information generated in this study serve as the useful tool for water sources protection such as recharge areas. Additionally, the findings can be used by water and land management experts in Usangu catchment to assess future water resources scenarios and hence prepare future based water and land management plans that are appropriate for reducing water stress among the competing users both within and the downstream of Usangu catchment.

1.2.3 Research Objectives

The general objective of this study was to evaluate the impacts of future climate and land use changes on surface-subsurface water balance in Usangu catchment.

Specifically, the study aimed to:

- i. establish the origin, flow pathways and interconnections of surface and subsurface waters in Usangu catchment.
- ii. predict the future land use and cover change of Usangu catchment using Markov Chain and Cellular automata models
- iii. assess the future impacts of climate and land use and cover changes on surface-subsurface water balance.
- iv. evaluate the effectiveness of some water and land management practices as the remedies for the adverse impacts of future land use and climate changes on water resources

1.2.4 Research questions

In the pursuit of the objectives of this study, answers to the following key questions, were sought.

- i. What is the origin, flow pathways and hydrological interconnections among waters in different sources in the catchment?
- ii. What will be the major land use and cover changes in Usangu catchment by 2020?
- iii. How will the future land use/cover and climate changes interact to influence surface-subsurface water balance in the catchment?

- iv. What are the most effective water and land management practices to mitigate the dwindling water resources in the catchment due to the impact of land use/cover and climate change?

In order to achieve the study objectives and answer the research questions, several activities were carried out as summarised in Fig. 1.

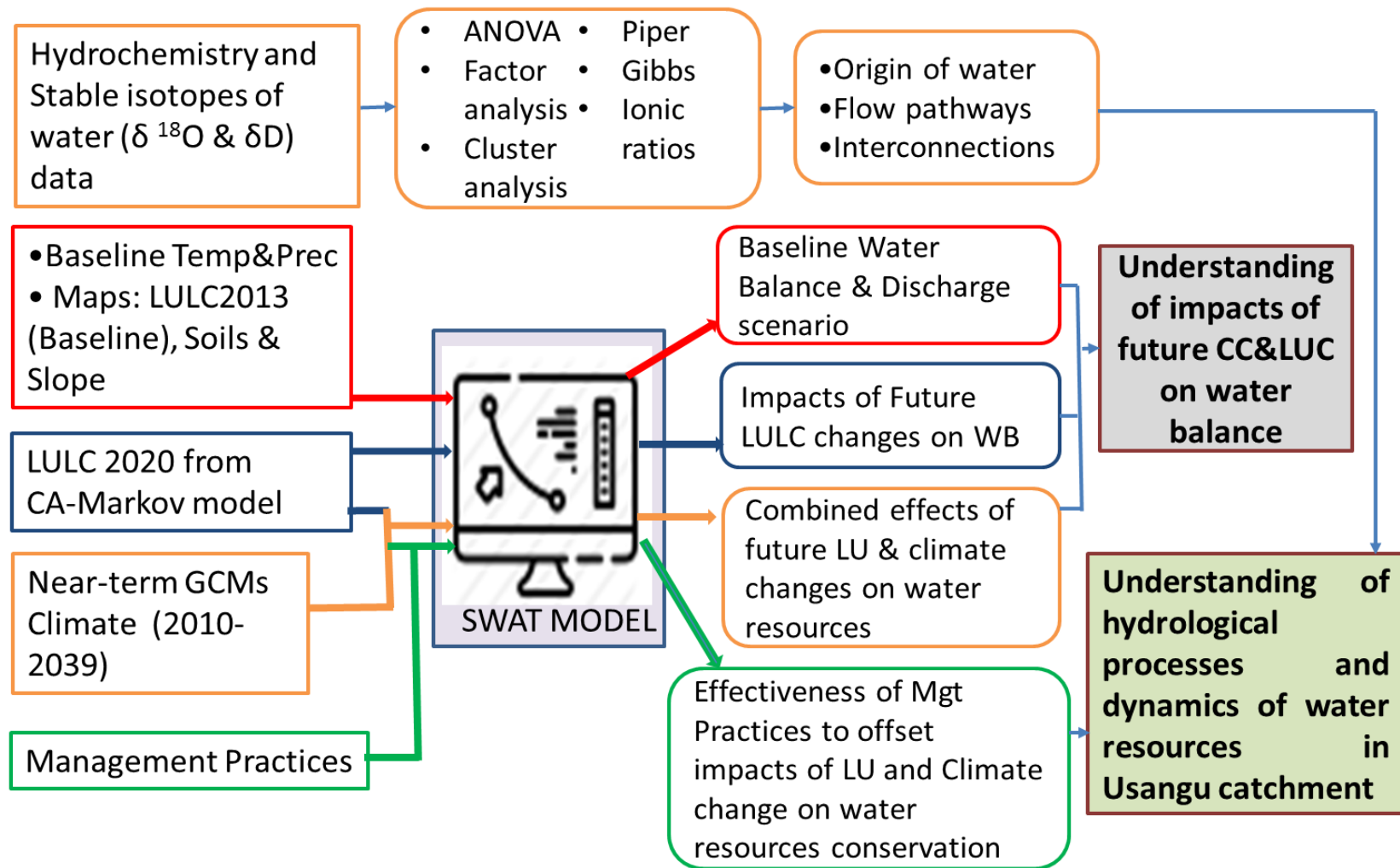


Figure 1: Summary of data, steps, processes involved in the study and their outcomes

1.3 Structure of the dissertation

The dissertation is written in a manuscript format, comprised of five chapters whereby two chapters have been published in the science peer review journals. The summary of each chapter of the dissertation is as follows;

Chapter 1 provides the general introduction of the interrelations between land use and climate changes and water resources dynamics both within and outside Usangu catchment. In addition, the chapter presents the problem statement and justification, significance of the research, objectives and the conceptual framework of the research. Chapter 2 presents the applications of the stable isotopes compositions of water (^{18}O and ^2H), major dissolved ions (K^+ , Na^+ , Mg^{2+} , Ca^{2+} , Cl^- , CO_3^{2-} , SO_4^{2-}) and dissolved silica (SiO_2) for rainfall, rivers, springs and wells to characterize hydrological processes in the Usangu catchment.

Chapter 3 uses a Markovian and Cellular Automata (MC-CA) models to predict future (20202) land cover scenario of Usangu Catchment. A paper titled “A Markovian and cellular automata land-use change predictive model of the Usangu Catchment” has been published in International Journal of Remote Sensing, 38(1):64-81. DOI: 10.1080/01431161.2016.1259675.

Chapter 4 uses Soil and Water Assessment Tool (SWAT) to simulate the impact of future climate and land use/cover change on water resources in the Ndembera watershed (one of river watersheds in Usangu catchment). In addition, the chapter evaluates the effectiveness of land and water management practices (filter strips, contour and terracing, grassed waterways and deep ripper tillage) as the mitigation strategies for the impacts of land use/cover and climate changes. One paper titled “The impact of future climate and land use/cover change on water resources in the Ndembera watershed and their mitigation strategies” has been published in Environmental Systems Research Journal, <https://doi.org/10.1186/s40068-018-0110-4>.

Chapter 5 provides a general discussion of all the findings in the dissertation. Further, the general conclusions, scientific contribution and recommendations are presented in this chapter.

CHAPTER TWO

Characterization of surface-groundwater hydrological processes in Usangu catchment: Isotopic and hydrochemistry perspective

Abstract

The stable isotopes compositions of water (^{18}O and ^2H), major dissolved ions (K^+ , Na^+ , Mg^{2+} , Ca^{2+} , Cl^- , CO_3^{2-} , SO_4^{2-}) and dissolved silica (SiO_2) for rainfall, rivers, springs and wells were used to characterize hydrological processes in the Usangu catchment. Analysis of variance, Hierarchical Cluster Analysis, factor analysis and the Piper diagram were used to determine hydrochemical facies to delineate the origin, flow paths of water and interconnections among water sources. The abundance of dissolved ions in water sources were in the order of $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ and $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{CO}_3^{2-}$, whereby the highest ions concentration occurred in wells, and differed significantly from that of rivers and springs at 95% confidence level due to prolonged water-rock interactions, suggesting two different subsurface water flow pathways. Low dissolved ions and silica that did not differ significantly at 95% confidence level, as well as their co-existence in the same hydrochemical water clusters suggested a close river-spring hydrological connection. Furthermore, factor analysis showed that 52.8% of variations in water sources was explained by dissolution of carbonate and silicate minerals, indicated by Ca^{2+} , Mg^{2+} , Na^+ , SO_4^{2-} , HCO_3^- , SiO_2 , Cl^- and CO_3^{2-} , most of which constituted the major hydrochemical facies, and 20.3% by source effects indicated by $\delta^{18}\text{O}$ and δD . The overall mean $\delta^{18}\text{O}$ and δD values in rainwater (-4.2‰ and -27.7‰), rivers (-4.0‰ and -25.0‰), springs (-5.6‰ and -32.5‰) and wells (-4.6‰ and -27‰) did not differ significantly at 95% confidence level, suggesting a recent recharge. However, the water in wells were slightly enriched in ^{18}O compared to spring and rivers. Further, water in wells had high SiO_2 concentrations that correlated positively with $\delta^{18}\text{O}$ values at 95% confidence level ($r^2=0.96$), attributed to prolonged rock-water interactions along the sub-surface flow path. Further studies involving geophysical survey to map specific type and exact depth of aquifers are recommended for better understanding of water resources in the watershed to enable proper water resources use, planning and protection.

Keywords: Surface-groundwater, Hydrological processes, Environmental isotopes, Hydrochemistry, Usangu Catchment

2.1 Introduction

Understanding a watershed hydrological processes such as water origin, flow pathways and interconnections, is essential for strategic management of surface and groundwater resources (Sophocleous, 2002; Hrachowitz *et al.*, 2011). Recently, considerable advances have been made in the understanding of watershed hydrological process using various tracer tools such as stable isotopes of water (Deuterium and Oxygen-18) and dissolved ions (Taylor and Howard, 1996; Mul, 2009; Bushman *et al.*, 2010; Hrachowitz *et al.*, 2011). In addition, the use of various statistical techniques such as multivariate analysis (factor analysis and cluster) (Thyne *et al.*, 2004; Belkhiri *et al.*, 2010; Bushman *et al.*, 2010) for analyzing the hydrochemical and stable isotopes data, have enabled the extraction of useful information for understanding catchment hydrological processes. Despite such advancements, these tools have not been widely applied in most of developing countries including the East African countries. Reliable long-term data in most of the watersheds in East African countries is not available which hinders rigorous and accurate water resources assessments (Mutenyo *et al.*, 2013), and formulation of effective water management policies (Howard and Karundu, 1992; Kashaigili, 2010; Mckenzie *et al.*, 2010).

The study on assessment of groundwater availability in Tanzania showed that the quantification of the groundwater resources of the country has not yet been possible because of a lack of requisite data such as annual abstractions and recharge (Kashaigili, 2010). In most cases, the only available information has been extracted from existing borehole log data. The few available hydrogeological data are scattered, fragmented and usually incomplete. As a result, groundwater resources management plans in Tanzania are not guided by rich scientific data. Many basin management organizations in East Africa face a similar lack of information on hydrogeology, water origins, and interconnections. The Usangu catchment in Tanzania is one of such catchments in East Africa where there are limited data and understanding of water sources, origins and hydrological interconnections.

The effective management of water resources in the East African catchments is urgently needed as they face threat from the projected climate change (Mckenzie *et al.*, 2010; Faramarzi *et al.*, 2013), land use change (Mulungu and Kashaigili, 2012), and increasing population (Sokile *et al.*, 2003; Parry, 2007). To be able to come up with effective strategies to manage water resources under these changes, a thorough understanding of the watershed

hydrological characteristics is crucial. It is critical to understand the relative contribution of surface and groundwater as well as surface-groundwater interactions. A better understanding of such surface-groundwater interactions has implications for the sustainability of water resources over years.

The Usangu catchment is important for Tanzania food base as it produces about 30% of Tanzanian rice (Shu and Villholth, 2012; Mbaga, 2015). It is endowed with five major perennial rivers (Ruaha, Kimani, Mbarali, Ndembera and Chimala), supporting many irrigation schemes in the mid and lowlands (SMUWC, 2001b). The water in the lowlands supports the wildlife in the Ihefu wetland and Ruaha National Park (Kadigi *et al.*, 2008). Despite the economic and ecological importance of the catchment, the hydrological characteristics such as the origin of water, the flow pathways, and hydrological connection (groundwater-surface water interactions) are not adequately understood.

This study was carried out to describe the surface and subsurface hydrological processes in Usangu catchment. The hydrochemistry and isotopes composition data of waters were analyzed to delineate the origin of water, major flow pathways, and surface-subsurface hydrological connections. Furthermore, the study provides the information on the type of rock which water interacted with during the flow from recharge to discharge and the relative residence time of flow in the subsurface environment. The information generated in this study forms a baseline in understanding the hydrological processes in other within and out of East African regions with a similar tropical climate and data availability challenge for the easy formulation of water management strategies and policies.

2.2 Material and methods

2.2.1 Study area description

The Usangu catchment, which is located in the upper part of the Rufiji River Basin with an elevation of 1100-3000 meters above sea level (m.a.s.l), covers an area of 20,800 km². The catchment is within the East African Rift System (Mbede, 2002), surrounded by the Kipengere, Poroto and Chunya mountains in the South and Southern-east (Fig. 22). The South and South-eastern margin is marked by the Chimala fault scarp while on the West and North-west bound by a system of North-South striking step faults rising to the level of the uplifted Usangu fault scarp.

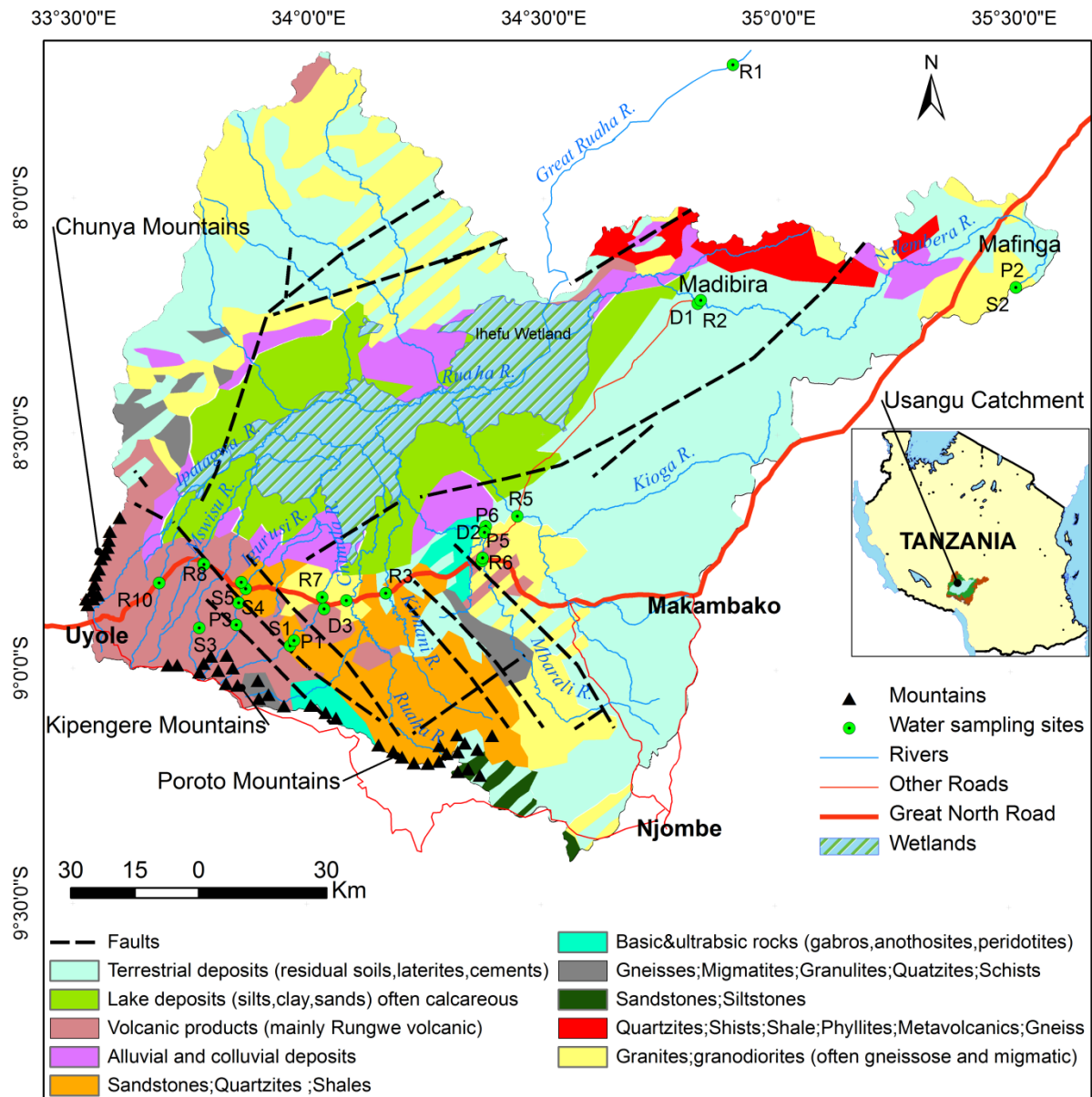


Figure 2: Map of Usangu catchment location showing rock types, sampling sites and other physical features (Source: Modified after Robert, 2013)

The Rungwe volcanics dominate a large part of South-west to southern part of the catchment. The Rungwe Volcanic rocks are dominated by a mixture of basalts, ash and pumice (Tumbo and Hughes, 2015). The terrestrial deposits (residual soils, laterites and cement) occupy large parts of the Usangu catchment and are mainly confined in the East, North and North eastern parts. Other geological formations such as the granitic rocks, sandstones, gneisses, basic and ultrabasic (gabbro, anorthosite and peridotites) are distributed in different parts of the catchment. The lake deposits occupy an area within and around Ihefu wetland, consisting of heterogeneous buried river channel and floodplain deposits, which are generally less

permeable than the surrounding alluvial fans. The fluvial-alluvial fans are important due to their groundwater potential related to relatively permeable geology and recharge from the surrounding mountain areas (SMUWC, 2001a).

The climate of the area is characterized by uni-modal rainfall which starts in November/December and ends in April/May. The surrounding highlands are considered as the groundwater recharge areas as they receive the heaviest rainfall in Tanzania (SMUWC, 2001a). Rainfall in the highlands is about 1600 mm/year, while in the plains it is around 500-700 mm/year (Shu and Villholth, 2012). Because of high precipitation, most of the rivers in Usangu catchment area which feed the Great Ruaha river, originate from the highlands (Kadigi *et al.*, 2008). The runoff generated from the highlands feeds the alluvial and seasonally flooded Usangu Plains, including the Ihefu wetland (Tumbo and Hughes, 2015).

2.2.2 Fieldwork

Fieldwork to collect water samples for determination of the stable isotopes compositions of water ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) and hydrochemistry was carried out in February, April, June and November in 2014. The wells and springs were sampled in June and November (dry season) while precipitation was sampled in February and April (Wet season), in 2014. Samples were collected from springs (n=5), precipitation (n=6), rivers (n=10) and wells (n=3). Sampling of the rivers was done in all four sampling months. Determination of electric conductivity, pH and water temperature was carried out using a portable multiparameter equipment (*HACH Sension 5*). Information on the sampling sites and types of water source is given in Appendix 1. Water samples earmarked for ^{18}O and ^2H isotopes were stored in 18ml universal glass bottles (K14 82 UO) while those for hydrochemistry analysis were collected in duplicate for in 500ml high-density polyethylene (HDPE) plastic bottles. Samples were collected in duplicate because the water for anions determination needed acidification while water for cations determination did not. Water samples for cations analysis were acidified using 2mls Nitric acid to stabilize the anion concentrations. All samples were transported in a cool box from the field to the laboratory for storage in a refrigerator at 6 degrees Celsius before analysis. The groundwater was sampled in wells (20 - 100m deep) after pumping out water for 15 minutes to prevent sampling the stagnant water in the well. Rainwater samples were collected using a 10L bucket with a funnel on top. The bucket was placed in an open space

whenever it rains, and the rain water of the whole rain event was collected. The time taken to collect rain water samples depended on the length of the time of a single rainfall event in a given day. Immediately after the rain, 18mls of the precipitation sample was poured in glass bottles, then closed using a metallic cap with plastic seals inside and firmly closed using Parafilm to prevent evaporation. The same type of bottles were used for collection of water samples from springs and wells for stable isotopes analysis. No acid buffer was added to stabilize samples for stable isotopes analysis.

2.2.3 Laboratory Analysis

Stable isotopes compositions of Oxygen and Hydrogen

Determination of the stable isotopes compositions of water was carried out using an off-axis integrated cavity output spectroscopy (OA-ICOS); model DLT-100, laser isotope analyzer (Los Gatos Research) at the Department of Water Management, Delft University of Technology in the Netherlands. Results are reported in δ -notation relative to Vienna Standard Mean Ocean Water (VSMOW). The $\delta^{18}\text{O}$ and δD results were compared with the Local Meteoric Water Line (LMWL) which was established using isotope data in precipitation from different parts of Tanzania (Fig. 3). The isotopes data in precipitation were obtained from the Global Network for Isotopes Precipitation (GNIP), (www.iaea.org/water) (Schotterer, 1996), and from published reports (Nkotagu and Mwambo, 2000; McKenzie *et al.*, 2010; Ghiglieri *et al.*, 2012).

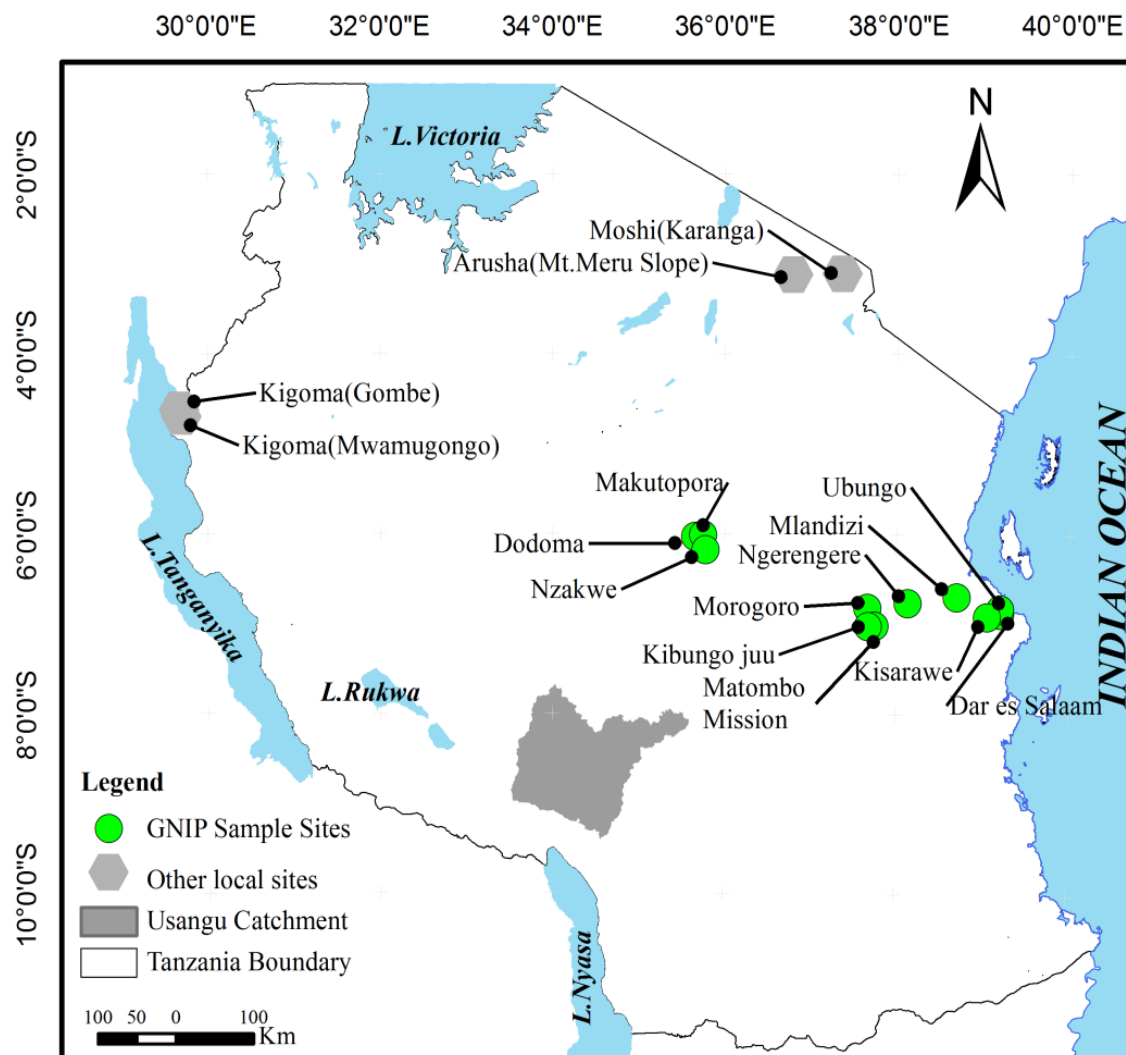


Figure 3: Locations in Tanzania where $\delta^{18}\text{O}$ and δD data for LMWL fitting were obtained.

The fitted LMWL is shown as insertion (top left corner) in Fig. 9.

Dissolved ions and Silica

Determination of major dissolved ions (Mg^{2+} , Ca^{2+} , Cl^- , CO_3^{2-} , SO_4^{2-} and Dissolved Silica (SiO_2) was carried out at the Ngurdoto Defluoridation Water Laboratory in Arusha, Tanzania, while the K^+ and Na^+ ions were analyzed at the Southern and East Africa Mineral Centre (SEAMIC). The determination of major dissolved ions was made for all water samples except rain water. Duplicate measurements were made for each sample to ensure precision and accuracy of results. Three methods (titration, Spectrometry, and Atomic Absorption Spectrophotometry) were employed for the determination of ion concentration. The titration method was used for total alkalinity, total hardness, Cl^- and Ca^{2+} ion, while spectrometer (DR/890 Colorimeter) was used to determine SO_4^{2-} and dissolved Silica (SiO_2) concentrations. The K^+ and Na^+ ions were analyzed using Atomic Absorption

Spectrophotometer (AAS), while Mg^{2+} , HCO_3^- and CO_3^{2-} were determined using the mathematical formulae provided by Trussell, et al., (1989).

$$Mg^{2+} (mg/L) = [Total\ Hardness - CaOH] * 0.243 \quad (1)$$

$$\frac{HCO_3^-}{Total\ alkalinity} = 5.0 * 10^{(pH-10)} \quad (2)$$

$$CO_3^{2-} = 0.94 * [Bicarbonate] * 10^{(pH-10)} \quad (3)$$

2.2.4 Data Quality Assessment

To ensure the quality of the hydrochemistry data, the devices (*HACH Sension 5* equipment and Spectrometer) were calibrated prior to their use. The standardization of titration chemicals (for example $AgNO_3$) was done before their use. Then, titration was done using a control sample (sample of a known concentration, example 100mg/l Cl^-). The accuracy of the spectrometer used for SO_4^{2-} and SiO_2 concentration measurements was calibrated using a blank sample (distilled water). The quality of isotopic water analysis results was checked by using the standard deviation values ($\delta^2H < 2\text{‰}$ and $\delta^{18}O < 0.3\text{‰}$). The sample with a standard deviation greater than these values was reanalyzed.

2.2.5 Data Analysis

In order to determine hydrochemical facies, Principal Component Factor Analysis (Dalton and Upchurch, 1978), Hierarchical Cluster Analysis (Yidana *et al.*, 2008) and Analysis of Variance (ANOVA) test were carried out on the water chemistry data. The ANOVA test was followed by a Tukey HSD test to find out which specific water sources' means (compared with each other) are different. Also trilinear diagram according to Piper (Piper, 1944) were used to classify water based on major cations and anions contents. The Gibbs diagram (Gibbs, 1970) and ionic ratios of some parameters such as Ca^{2+}/Mg^{2+} , Na^+/Cl^- , Na^+ versus Cl^- , and SiO_2 versus $\delta^{18}O$ were used to determine the chemical and ionic exchange processes controlling dissolved ions content of water. The bivariate scatter plots of $\delta^{18}O$ versus δ^2H were used to assess the source of water in various water sources as well as the mixing pattern among them. This was done so as to establish hydrological characteristics of the watershed such as the flow patterns, source origins, hydrological connections and chemical histories of surface and subsurface water masses.

2.3 Results

2.3.1 Physical parameters (TDS, pH and EC) and SiO₂ constituents in water sources

The mean concentration of TDS was highest in waters from wells which averaged about 245.9 mg/l, and almost similar in the river and springs, that is, 42.9 mg/l and 44.9 mg/l, respectively (Fig. 4a). The TDS concentration in the wells, spring and rivers ranged from 47.0 mg/l to 392.0 mg/l, 4.5 mg/l to 121.3 mg/l and 6.1 mg/l to 141.1 mg/l, respectively. The pH in springs averaged 6.7, which is slightly acidic, while in rivers and wells it averaged 7.0 and 7.1 (Fig. 4b). The wells had a narrow pH range (6.4 to 7.6) compare to rivers and springs (5.9 to 8.1 and 5.3 to 7.7, respectively). The EC was also highest in wells (491.5 μ S/m) and slight different values in rivers and springs which averaged 86.0 μ S/m and 89.8 μ S/m, respectively (Fig. 4c). The differences between minimum and maximum EC values in Fig. 4c was wider in wells (690.0 μ S/m) and narrow in river and springs (270.8 μ S/m and 233.9 μ S/m, respectively). Similarly, the SiO₂ concentrations in Fig. 4d showed a trend which was more or less the same as TDS and EC, that is, highest in wells (57.2 mg/l), and almost equal for rivers and springs (20.6 mg/l and 20.4 mg/l, respectively). Generally, there was a similar trend in the mean concentration of TDS, EC and SiO₂ in the three water sources, that is Wells>Rivers $\cong$ Springs (Fig. 4a, c and d).

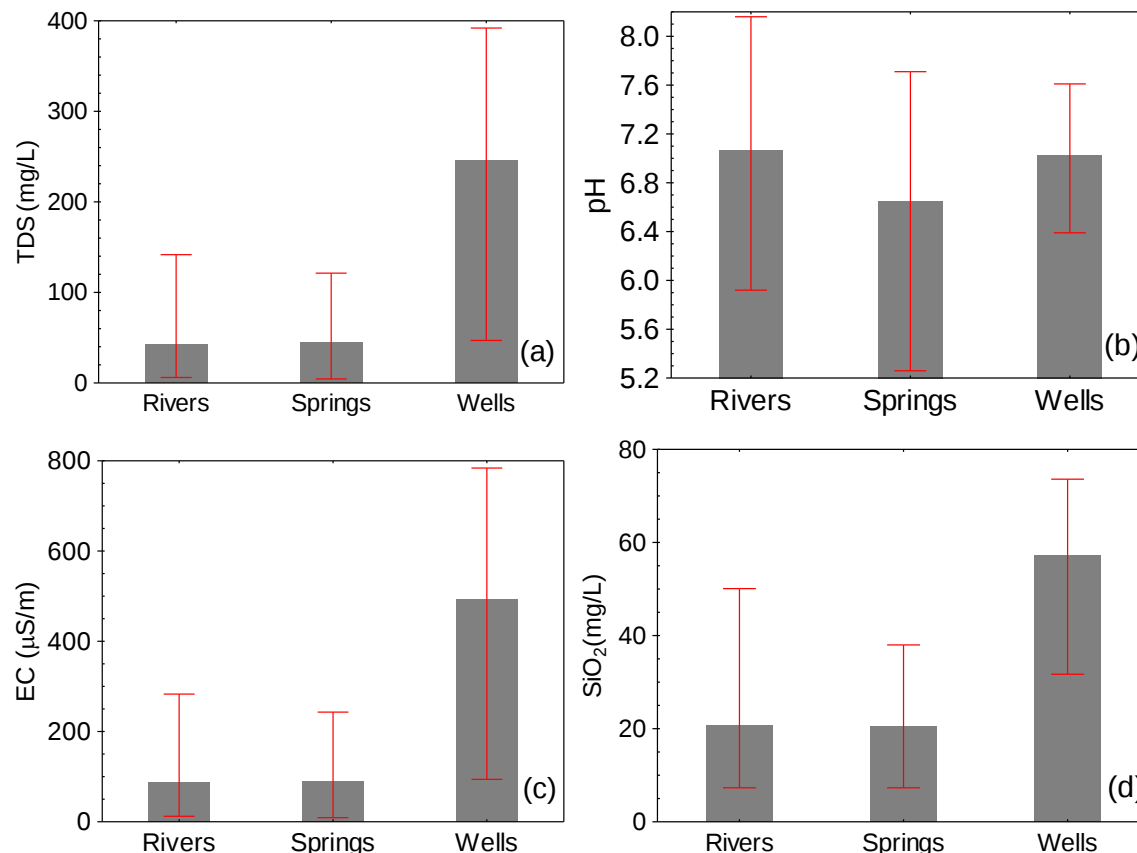


Figure 4: The mean values of TDS (a), pH (b), EC (c) and dissolved Silica (d) in water sources for all seasons. The whiskers show the minimum and maximum values

2.3.2 Major dissolved cations

The mean Ca^{2+} concentration was higher in wells (27.3 mg/l) relative to rivers (7.5 mg/l) and springs (8.2 mg/l) (Fig. 5a). The K^+ mean concentrations showed some narrow differences between rivers and springs (3.2 mg/l and 3.3 mg/l, respectively). River and springs had almost similar minimum (0.6 mg/l and 0.9 mg/l) and maximum (9.1 mg/l and 9.2 mg/l) K^+ concentration values. The mean K^+ concentration in wells averaged about 5.2 mg/l and a range of 5.5 mg/l between minimum and maximum values (Fig. 5b). Furthermore, Na^+ concentration in wells averaged about 95.5 mg/l, which was about 8 times higher than that of rivers and springs (12.2 mg/l and 12.4 mg/l, respectively) (Fig. 5c). For Mg^{2+} ion, its concentration in the wells, springs and rivers averaged 8.8 mg/l, 4.1 mg/l and 2.8 mg/l, respectively (Fig. 5d).

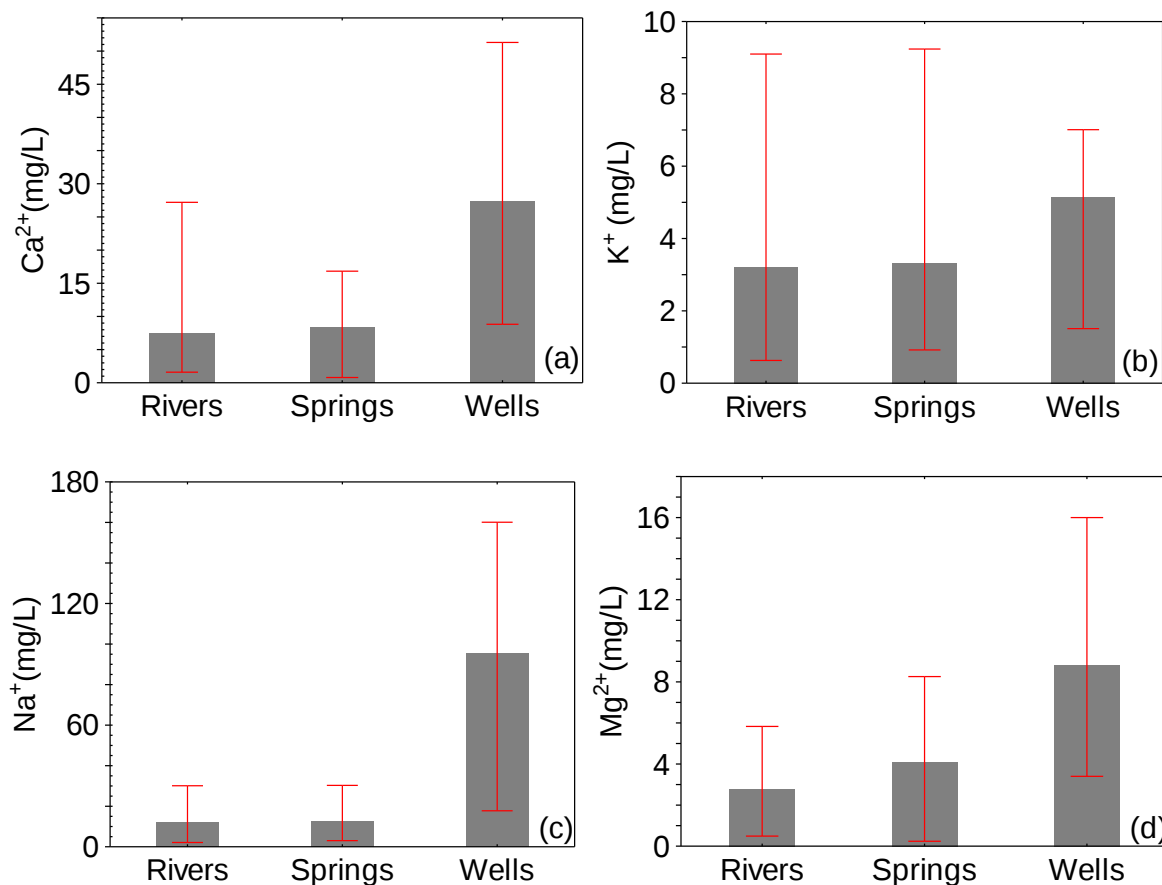


Figure 5: The mean concentrations of major cations in the water sources for all seasons. The whiskers show the minimum and maximum values

2.3.3 Major dissolved anions

The concentration HCO_3^- in waters from wells averaged 213 mg/l, which was almost seven times higher than that of springs (30.2 mg/l), and about six times than that of rivers (36.3 mg/l) as shown in Fig. 6a. The average value of CO_3^{2-} among the three water sources did not exceed 0.5 mg/l, and had a wider range in river and well sources (~ 1 mg/l) (Fig. 6b). Its average values in rivers, springs and wells were 0.1 mg/l, 0.1 mg/l and 0.4 mg/l, respectively. The SO_4^{2-} mean concentrations were very low in rivers and springs (0.8 mg/l and 1.1 mg/l, respectively) relative to wells which averaged 16.2 mg/l (Fig. 6c). The Cl^- mean concentration in the wells was also higher (20.5 mg/l) compared to springs and rivers which averaged 9.6 mg/l and 5.8 mg/l, respectively (Fig. 6d). The mean, minimum and maximum concentrations of Cl^- in Fig. 6 were in the order of wells>springs>rivers.

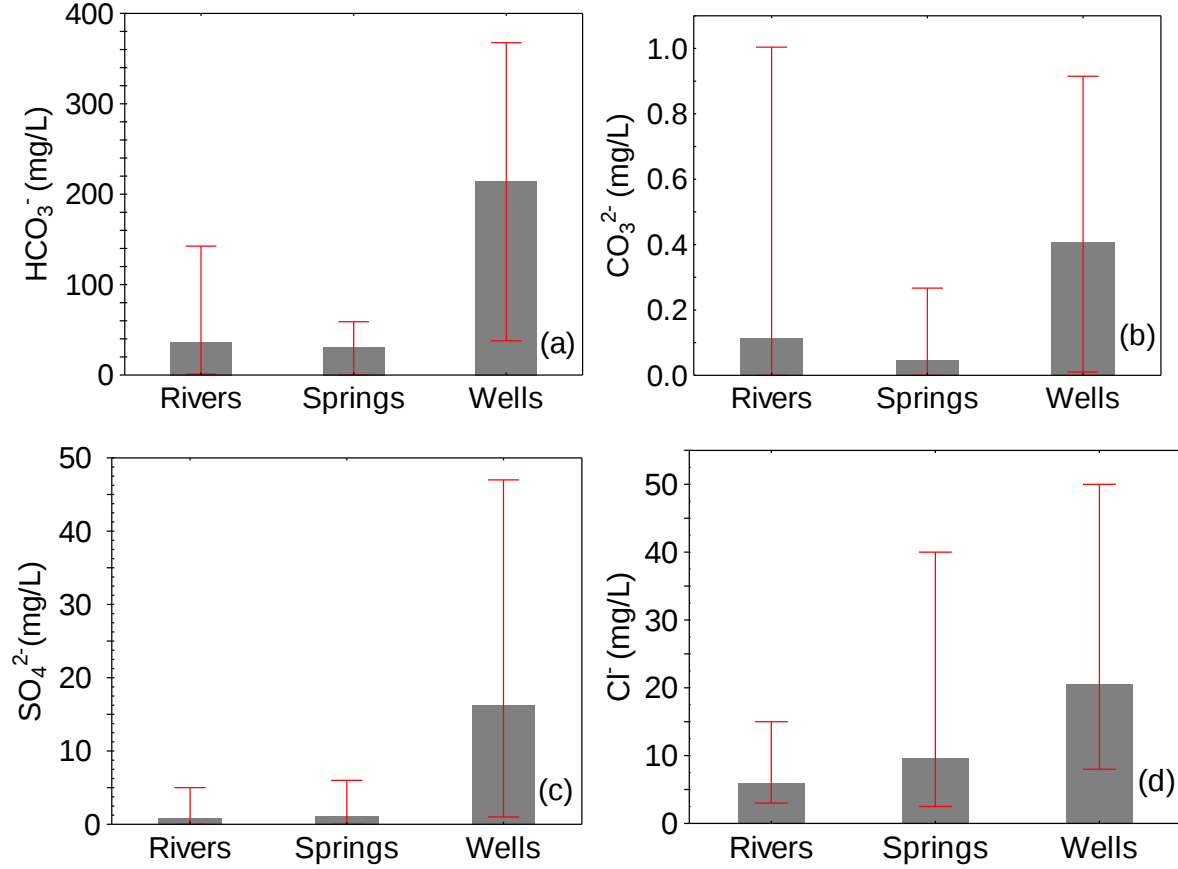


Figure 6: The mean concentrations of major anions in the water sources for all seasons. The whiskers show the minimum and maximum values

A general trend of results of physical-chemical and ions concentrations in Fig. 4 - 6 showed that the waters from wells had the highest mean values for all parameters (except K^+ , Fig. 5b). For example, the mean concentration of most of the parameters namely TDS, SiO_2 and EC (Fig. 4a,c&d), Ca^{2+} , K^+ (Fig. 5a&b) and SO_4^{2-} (Fig. 6c) were in the order of Wells>Rivers≈Springs. Also, the concentrations of Cl^- (Fig. 6d) and Mg^{2+} (Fig. 5d) were in the order of Wells>Springs>Rivers. Furthermore, the HCO_3^- and CO_3^{2-} ions concentrations among the three water sources were in the order of Wells>Rivers>Springs (Fig. 6a&b).

2.3.4 Stable isotopes of water ($\delta^{18}O$ and δD)

The mean $\delta^{18}O$ and δD isotopic composition in each source in Fig. 7a&b showed that $\delta^{18}O$ and δD values in all rain waters in the catchment averaged about -4.2‰ and -27.7‰, respectively. Generally, the springs had lower $\delta^{18}O$ and δD mean concentrations (-5.6‰ and -32.5‰) compared to the wells which averaged -4.6‰ and -27‰, respectively. River waters were slightly enriched compared to other sources with $\delta^{18}O$ and δD mean values of -4.0‰

and -25.0‰, respectively (Fig. 7a&b). In general, the mean concentrations of $\delta^{18}\text{O}$ in the four water sources were in the order of Rivers>Rain>Wells>Springs, while for δD was Rivers>Rain $\approx$ Wells>Springs. A wider range of $\delta^{18}\text{O}$ and δD concentrations was found in river and rain waters. The δD concentration ranged from -36.3‰ to 20.9‰ in rivers and -58.0‰ to 20.0‰ in rain waters. The $\delta^{18}\text{O}$ concentrations ranged from -5.5‰ to 5.5‰ in rivers and -7.2‰ to 1.1‰.

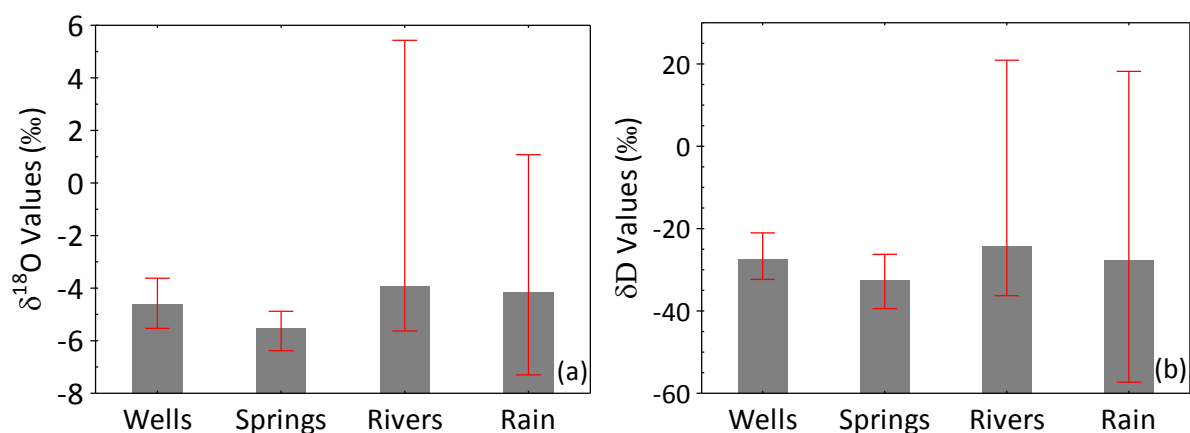


Figure 7: The mean concentrations of ^{18}O (a) and ^2H (b) in water sources for all seasons. The whiskers show the minimum and maximum values

2.3.5 Source and seasonal variations of water chemical and physical parameters

The analysis of variance (ANOVA) results in Table 1 revealed a significant source variation of most of the parameters except K^+ , $\delta^{18}\text{O}$ and δD ($p < 0.05$). Also, seasons (months of sampling) had no significant effects on water hydrochemistry, except pH. The Tukey-HSD post hoc test results (Table 2) showed that chemistry of water from wells differed significantly from that of springs and rivers at 95% confidence level, with a big difference in their means (I-J). On the contrary, spring and rivers did not reveal the significant mean differences for all parameters at 95% confidence level.

Table 1: The effects of water sources and sampling seasons on hydrochemical parameters

Parameter	Water Sources					Seasons				
	DF	SS	F	P	S/NS	DF	SS	F	P	S/NS
Ca ²⁺	2	1539.64	13.19	0.00	S	3	340.65	1.95	0.14	NS
Na ⁺	2	3 2354.23	30.16	0.00	S	3	74.83	0.05	0.99	NS
Mg ²⁺	2	192.83	16.07	0.00	S	3	18.44	1.03	0.39	NS
K ⁺	2	19.13	1.55	0.22	NS	3	5.31	0.29	0.83	NS
HCO ₃ ⁻	2	14 7519.30	25.47	0.00	S	3	1717.90	0.20	0.90	NS
CO ₃ ²⁻	2	0.50	6.33	0.00	S	3	0.26	2.21	0.10	NS
Cl ⁻	2	908.60	8.25	0.00	S	3	63.80	0.39	0.76	NS
SO ₄ ²⁻	2	1085.68	8.40	0.00	S	3	2.22	0.01	1.00	NS
SiO ₂	2	6440.09	25.71	0.00	S	3	171.30	0.46	0.71	NS
TDS	2	18 5150.11	29.54	0.00	S	3	2672.30	0.28	0.84	NS
EC	2	73 9571.73	29.52	0.00	S	3	1 0590.90	0.28	0.84	NS
pH	2	3.84	6.07	0.01	S	3	6.68	7.04	0.00	S
δD	3	591.15	0.98	0.41	NS	3	180.02	0.30	0.83	NS
δ ¹⁸ O	3	19.29	1.36	0.27	NS	3	3.43	0.24	0.87	NS

S = Significant, NS = Not Significant, DF = Degree of Freedom, SS = Sum of Squares, F = F value, P = p value

Table 2: Tukey HSD Multiple Comparison results

Parameter	(I) Source	(J) Source	Mean Difference (I-J)	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Na ⁺	Rivers	Springs	-0.14	1.000	-20.47	20.19
		Wells	-83.27*	.000	-108.26	-58.27
	Springs	Rivers	0.14	1.000	-20.19	20.47
		Wells	-83.13*	.000	-112.21	-54.04
Ca ²⁺	Rivers	Springs	-0.83	.952	-7.53	5.88
		Wells	-19.80*	.000	-28.04	-11.55
	Springs	Rivers	0.83	.952	-5.88	7.53
		Wells	-18.97*	.000	-28.56	-9.38
Mg ²⁺	Rivers	Springs	-1.28	.327	-3.43	.87
		Wells	-6.04*	.000	-8.69	-3.40
	Springs	Rivers	1.28	.327	-.871	3.43
		Wells	-4.76*	.001	-7.84	-1.69
HCO ₃ ⁻	Rivers	Springs	6.08	.947	-41.15	53.31
		Wells	-177.61*	.000	-235.68	-119.54
	Springs	Rivers	-6.08	.947	-53.31	41.15
		Wells	-183.69*	.000	-251.26	-116.12
Cl ⁻	Rivers	Springs	-3.78	.345	-10.29	2.74
		Wells	-14.68*	.000	-22.68	-6.67
	Springs	Rivers	3.78	.345	-2.74	10.29
		Wells	-10.90*	.019	-20.22	-1.58
SO ₄ ²⁻	Rivers	Springs	-0.34	.992	-7.40	6.71
		Wells	-15.41*	.000	-24.08	-6.73
	Springs	Rivers	0.34	.992	-6.71	7.40
		Wells	-15.07*	.002	-25.16	-4.97
CO ₃ ²⁻	Rivers	Springs	0.07	.631	-.11	.24
		Wells	-0.29*	.005	-.51	-.08
	Springs	Rivers	-0.07	.631	-.24	.11
		Wells	-0.36*	.003	-.61	-.11
TDS	Rivers	Springs	-1.93	.995	-51.06	47.21
		Wells	-202.94*	.000	-263.35	-142.53
	Springs	Rivers	1.93	.995	-47.21	51.06
		Wells	-201.01*	.000	-271.31	-130.72

* The mean difference is significant at the 0.05 level.

2.3.6 Variations of $\delta^{18}\text{O}$ and δD composition in water sources

Rainfall

The $\delta^{18}\text{O}$ -elevation relationship showed as altitude increased, enrichment of $\delta^{18}\text{O}$ in rainwaters also increased, with a slope of +0.1 (Fig. 8a). Generally, the rain waters sampled from high altitudes such as Chimala (2005 m.a.s.l) were more isotopically enriched (-4.7‰

and -3.3‰), compared to Rujewa Met (-7.3‰ and -6.9‰), at the lowest elevation of 1082 m.a.s.l. In contrary, the δD -elevation relationship showed that as elevation increased the rainwater was more depleted, showing a slope of -0.3 (Fig. 8b).

Seasonally, the rainwater for February were more depleted in $\delta^{18}O$ and δD values than April, for all stations, except Mswisu (Fig. 8a&b). For example, the $\delta^{18}O$ compositions of rain waters from Mswisu for the months of February and April were 1.1‰ and -7‰, respectively. Similarly, δD values for the same station (Mswisu) in the two months were 3.2‰ and 43.6‰, respectively. Again, Igawa met station showed high enrichment $\delta^{18}O$ and δD isotopes in the month of April compared to other stations ($\delta^{18}O = 0.8‰$ and $\delta D = 18.2‰$).

Springs

Both $\delta^{18}O$ -elevation and δD -elevation relationships for spring waters showed the higher the altitude, the more depleted $\delta^{18}O$ and δD values (Fig. 8c&d). The slopes of their trend lines were -0.17 and -1.4, respectively. The isotopic composition and elevation relationship for spring waters in Fig. 8c&d was more conspicuous than that of rainwaters in Fig. 8a&b.

Seasonal variations of both $\delta^{18}O$ and δD composition in waters from the five springs in the study area was very small (Fig. 8c&d). The differences in $\delta^{18}O$ values for November and June for stations such as Iloilo, Igurusi and Chimala springs were only about 0.4‰, 0.1‰, and 0.2‰, respectively. In addition, almost equal values were shown in June and November for some springs such Ndembera ($\delta^{18}O = -4.9‰$), and Chimala ($\delta D = -34.3‰$).

Wells

Similar to springs, there was an increasing trend of isotopic enrichment of well waters as the altitude increased, and the vice versa is true (Fig. 8e&f). The values of the slope were -0.5 (Fig. 8e) and -4.1 (Fig. 8f), respectively. Despite the fact that Chimala mission and Kabute wells were located on almost similar elevations (1078 m.a.s.l and 1079 m.a.s.l, respectively), Chimala mission well had more depleted isotope values ($\delta^{18}O = -5.5‰$ and $\delta D = -32.0‰$) than Kabute well ($\delta^{18}O = -3.6‰$ and $\delta D = -21.0‰$). Its waters were also more depleted than Joseph well ($\delta^{18}O = -4.6‰$ and $\delta D = -29.3‰$), located on the higher altitude of about 1169 m.a.s.l.

The waters in wells showed very small seasonal isotopic composition variations (Fig. 8e&f). For instance, Chimala mission had similar $\delta^{18}\text{O}$ values for November and June, that is -5.5‰. Similarly, the δD values for the same Chimala mission well in the two months were almost similar, that is, -32.3‰ and -31.9‰, respectively.

Rivers

The linear relationship between $\delta^{18}\text{O}$ and elevation values of water from rivers showed an increasing isotopic enrichment trend as altitude decreased (Fig. 8h). The slope of a trend line was -0.45. In this regard, the river waters from higher altitudes such as Ipatagwa (1,252 m.a.s.l) had the most depleted $\delta^{18}\text{O}$ values which averaged about -5.4‰. In the contrary, river waters of Ruaha River at Msembe (818 m.a.s.l) were most enriched among all rivers with average $\delta^{18}\text{O}$ values of about 0.7‰. Similarly, the δD -elevation relationship in Fig. 8g showed a slope of -2.6, whereby the higher the altitude, the more depleted δD values in the river waters.

The $\delta^{18}\text{O}$ enrichment trend in most of the rivers was in the order of November > February > April > June (Fig. 8h). For δD , the enrichment was in the order of November > June > February > April (Fig. 8g). Additionally, compared to other months, April and June had slightly depleted $\delta^{18}\text{O}$ and δD values for all rivers. In addition, waters of the Ruaha River (Msembe) were the most isotopically enriched throughout the year (Fig. 8g-h).

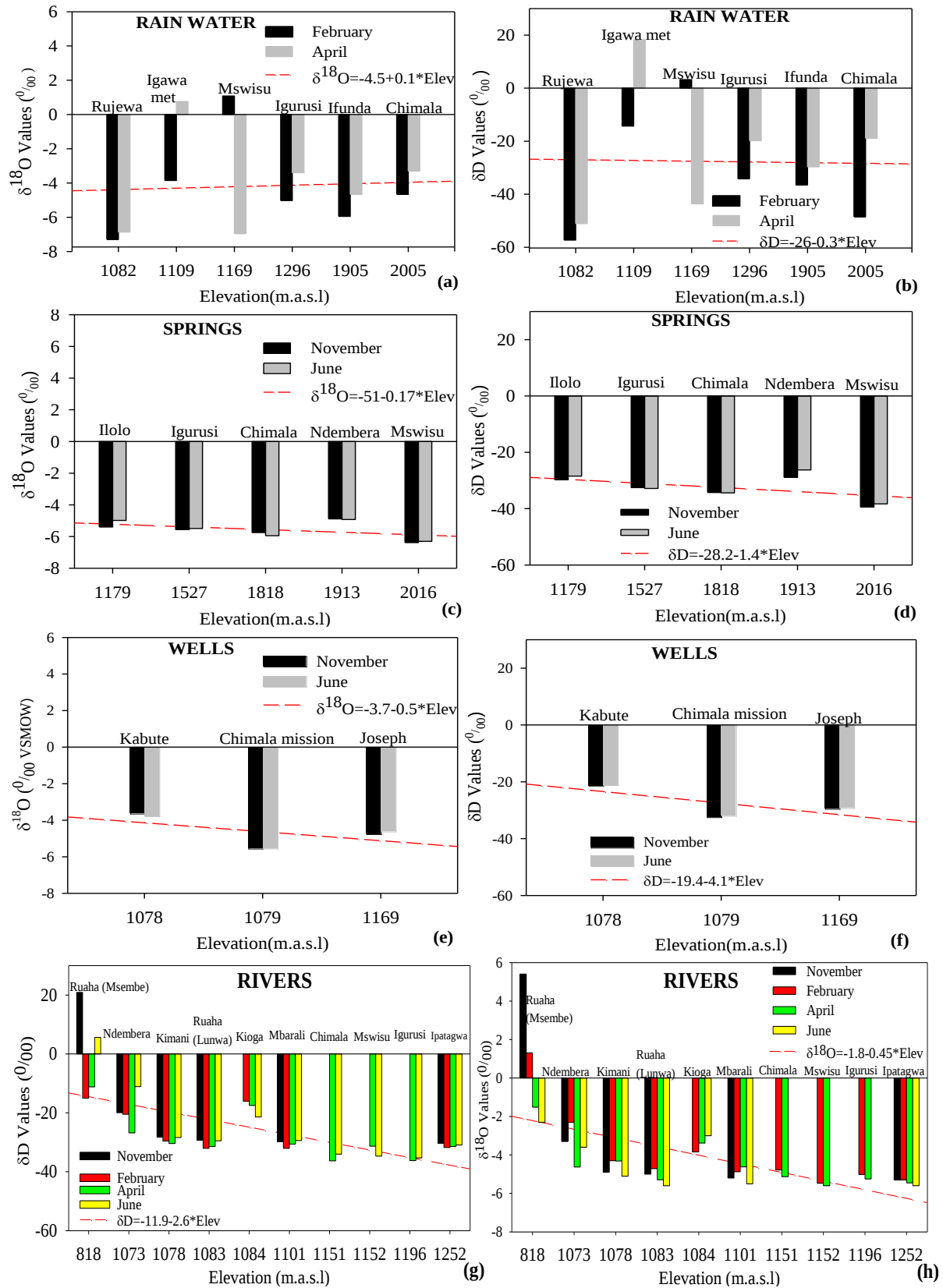


Figure 8: The $\delta^{18}\text{O}$ and δD composition in water from rain (a and b), springs (c and d), wells (e and f) and rivers (g and h)

A plot of δD vs. $\delta^{18}O$ values of all water sources sampled at different months showed that majority of water sources fell along the LMWL (Fig. 9). The expanded plot (Fig. 9b) demonstrated that majority of samples clustered between -6.5‰ to 4.9‰ ($\delta^{18}O$) and -20‰ to -40‰ (δD); with a mixed distribution pattern. In the cluster, most of springs and wells as well as some rivers (February, April and November) and rainwater (mainly February) plotted very close to the LMWL. Out of the cluster, the rainwater from Mswisu (February), Chimala (February) and Rujewa (February and April) were displaced far from the LMWL. In addition, The the enriched δD vs. $\delta^{18}O$ values of waters from rivers (Ndembera, Kioga and Ruaha-Msembe) fell on the evaporation line with a slope of 4.5. An insertion at the top left corner of Fig. 9a shows the fitted LMWL using data collected from parts of Tanzania as shown in Fig. 3.

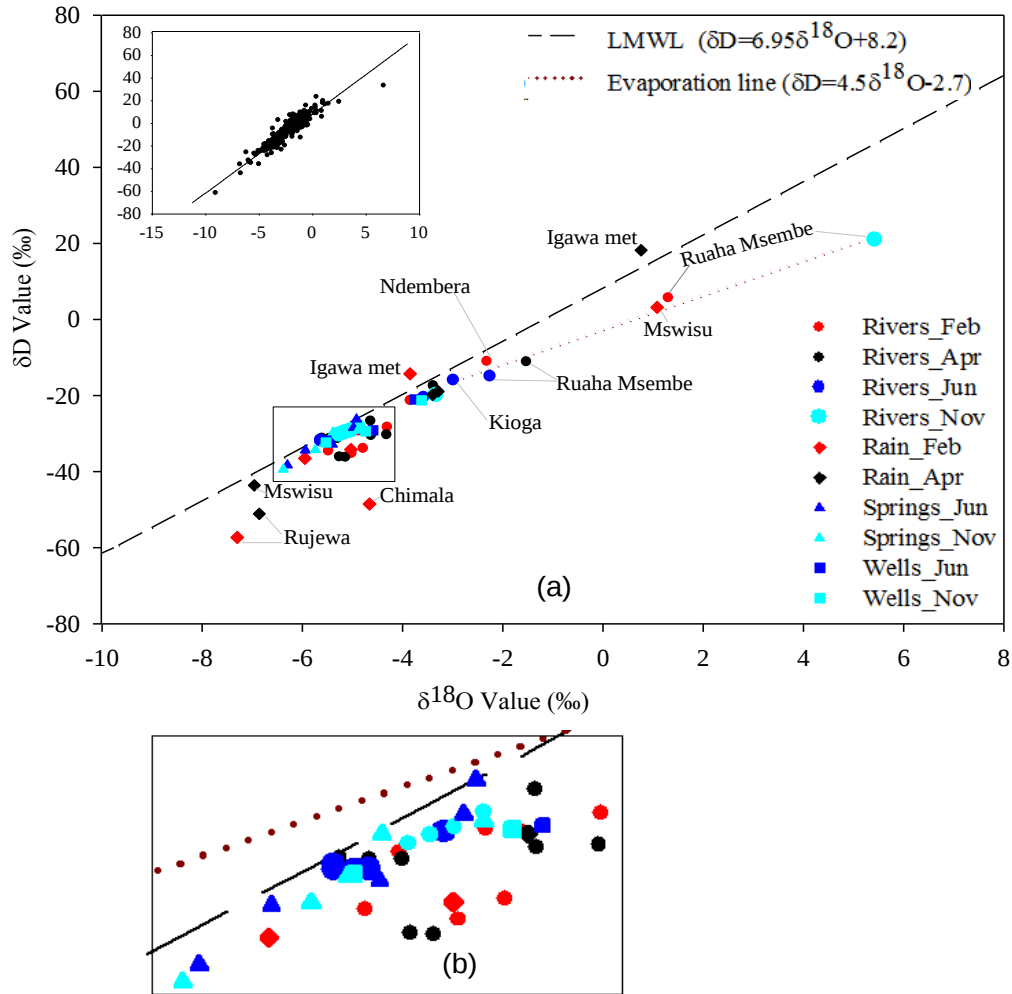


Figure 9: A plot of δ^2H versus $\delta^{18}O$ values of water samples along LMWL

2.3.7 Rock-water interactions and hydrochemical facies

Piper diagram grouped waters emanating from different geological formations in Usangu catchment in five hydrochemical facies based on their major cations and anions contents. The facies were Ca-HCO₃ (38.9%), Ca-Na-HCO₃ (22.2%) Na-HCO₃ (5.56%), Na-Cl (5.6%), and Ca-Mg-Cl (5.6%) (Fig. 10). Majority of water sources were of Ca-HCO₃ and Ca-Na-HCO₃ facies (61.0%) or a mixture of the two (11.1%). Water sources which plotted exactly on Ca-HCO₃ facies domain include Mswisu and Chimala springs, while for Ca-Na-HCO₃ were Chimala, Ipatagwa and Mswisu Rivers as well as Kabute well. Water in Chimala Mission Well was of a mixture of Ca-HCO₃ and Ca-Mg-Cl facies. Only two sources (Ndembera and Ilolo springs) showed the predominance of NaCl facies. Water in wells showed Ca-HCO₃ (33.3%), Na-HCO₃ (33.3%) and Ca-Na-HCO₃ (33.3%) water type; while springs showed predominance of Ca-HCO₃ (50.0%), and Ca-Na-HCO₃ (16.7%), Na-Cl (16.7%) and a mixture of CaNaHCO₃ and NaCl (16.7%). Major dissolved ions which constituted the predominant hydrochemical facies in Fig. 10, together with the physical chemical parameters and stable isotopes of water ($\delta^{18}\text{O}$ and δD) were correlated differently (Table 3). Taking the correlation coefficient (r) ≥ 0.75 ($p < 0.01$) as the strong correlation, the Ca^{2+} ion showed a positive and strong correlation with TDS, EC, TH and most of the dissolved ions except K^+ , CO_3^{2-} and SO_4^{2-} . Again, Na^+ showed a strong correlation with Cl^- , HCO_3^- , SO_4^{2-} , SiO_2 and EC. Furthermore, the EC and TDS were equally strongly correlated with Ca^{2+} , Na^+ , Cl^- , HCO_3^- and SiO_2 ($p < 0.01$).

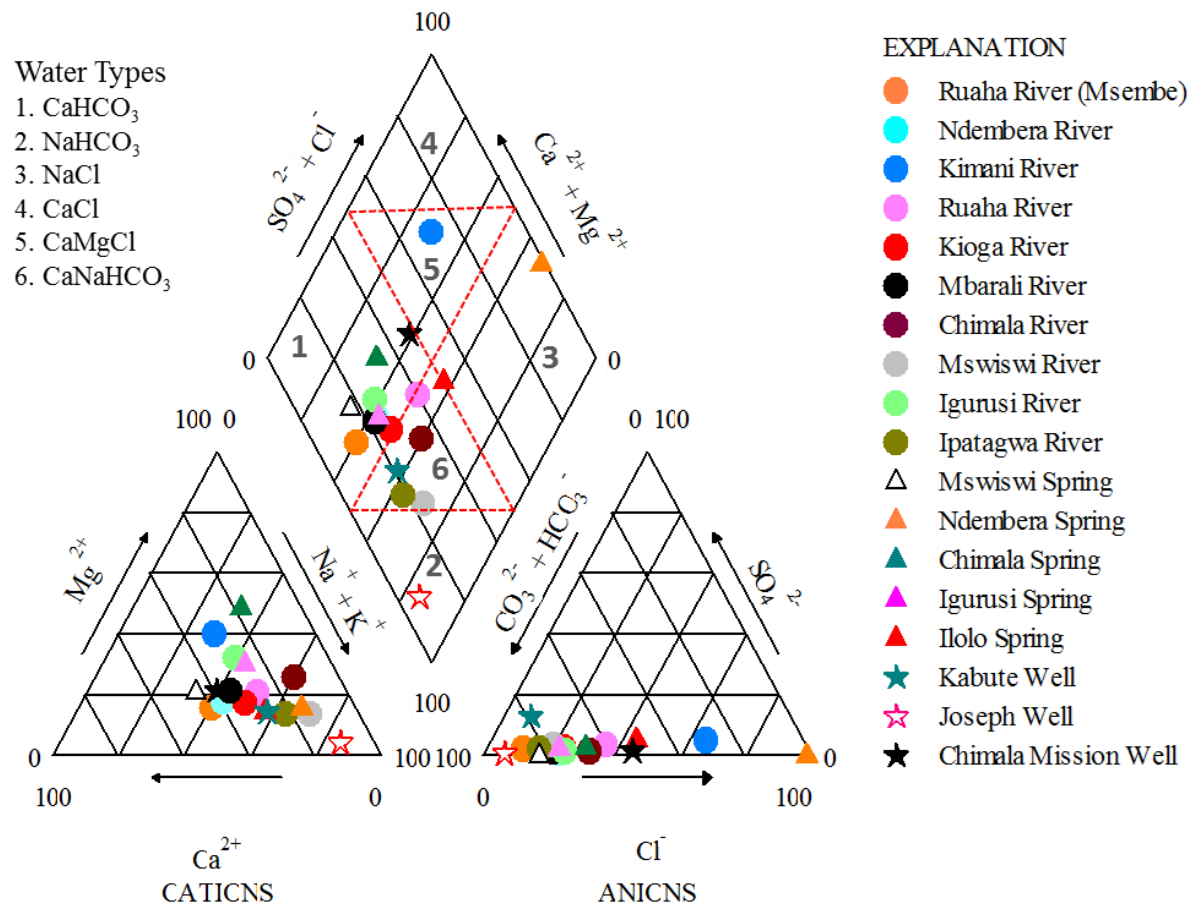


Figure 10: Piper diagram showing predominant facies for various water sources (Water type regions 1, 2, 3...6 are arranged according to Saravanan et al., 2015)

Table 3: Correlation coefficients matrix of water samples of Usangu catchment

	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	Cl ⁻	HCO ₃ ⁻	CO ₃ ⁻²	SO ₄ ²⁻	SiO ₂	TDS	EC	TH	δ ² H	δ ¹⁸ O	pH
Ca ²⁺															
Mg ²⁺	0.72**														
K ⁺	0.37	0.31													
Na ⁺	0.76**	0.62**	0.74**												
Cl ⁻	0.85**	0.64**	0.50*	0.82**											
HCO ₃ ⁻	0.92**	0.65**	0.50	0.87**	0.88**										
CO ₃ ⁻²	0.62**	0.40	0.23	0.61**	0.44	0.70**									
SO ₄ ²⁻	0.59*	0.58*	0.66**	0.77**	0.64**	0.69**	0.38								
SiO ₂	0.69**	0.61**	0.79**	0.89**	0.77**	0.74**	0.47*	0.61**							
TDS	0.91**	0.66**	0.52*	0.88**	0.92**	0.98**	0.62**	0.70**	0.80**						
EC	0.91**	0.66**	0.52*	0.88**	0.92**	0.98**	0.62**	0.70**	0.80**	1.00**					
TH	0.95**	0.87**	0.36	0.76**	0.84**	0.88**	0.54*	0.6**	0.69**	0.89**	0.89**				
δ ₂ H	0.26	-0.08	-0.01	0.22	0.26	0.36	0.39	0.40	-0.07	0.29	0.29	0.13			
δ ₁₈ O	0.05	-0.19	-0.20	0.08	0.16	0.27	0.37	0.17	-0.13	0.18	0.18	-0.05	0.82**		
pH	0.33	0.26	0.05	0.30	0.03	0.33	0.73**	0.24	0.15	0.23	0.23	0.29	0.06	0.01	

** . Correlation is significant at the 0.01 level (2-tailed)

* . Correlation is significant at the 0.05 level (2-tailed)

2.3.8 Factor analysis results

Factor analysis carried out on the dataset containing the physical chemical parameters, major cations and anions as well as $\delta^{18}\text{O}$ and δD composition of waters from wells, rivers and springs allowed the extraction of 11 factors (Table 4). Nevertheless; only four factors (components) had eigenvalues greater than 1. These four factors accounted for 95.0% of total variance in the dataset. Factor 1 explained more than half of the explained variance in the dataset (52.8%). The variance explained by the remaining three factors were 20.3%, 11.6% and 10.3%, respectively.

Table 4: Extracted Components (Factors), Eigenvalues and variance explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	5.81	52.85	52.85	5.81	52.85	52.85
2	2.23	20.27	73.12	2.23	20.27	73.12
3	1.27	11.56	84.68	1.27	11.56	84.68
4	1.14	10.33	95.01	1.14	10.33	95.01
5	0.27	2.41	97.42			
6	0.12	1.10	98.51			
7	0.07	0.65	99.16			
8	0.06	0.53	99.69			
9	0.02	0.18	99.87			
10	0.01	0.13	100.00			
11	0.00	0.01	100.00			

Extraction Method: Principal Component Analysis

The plot of Factor 1 versus Factor 2 in Fig. 11a showed that Factor 1 was characterized by highly positive loadings in Ca^{2+} , Mg^{2+} , Na^+ , SO_4^{2-} , HCO_3^- and SiO_2 ; meanwhile, the Cl^- and CO_3^{2-} ions demonstrated medium and positive loadings on Factor 1. The same Fig. 11a showed that the δD and $\delta^{18}\text{O}$ stable isotopes of water had highly positive loadings in Factor 2. Furthermore, the CO_3^{2-} had almost loading score on Factor 1 and 3 with the loading scores of 0.68 and 0.69, respectively (Fig. 11b). The plot of Factor 1 versus Factor 4 (Fig. 11c) showed that Factor 4 was characterized by positive but medium loadings in K^+ (score of 0.63).

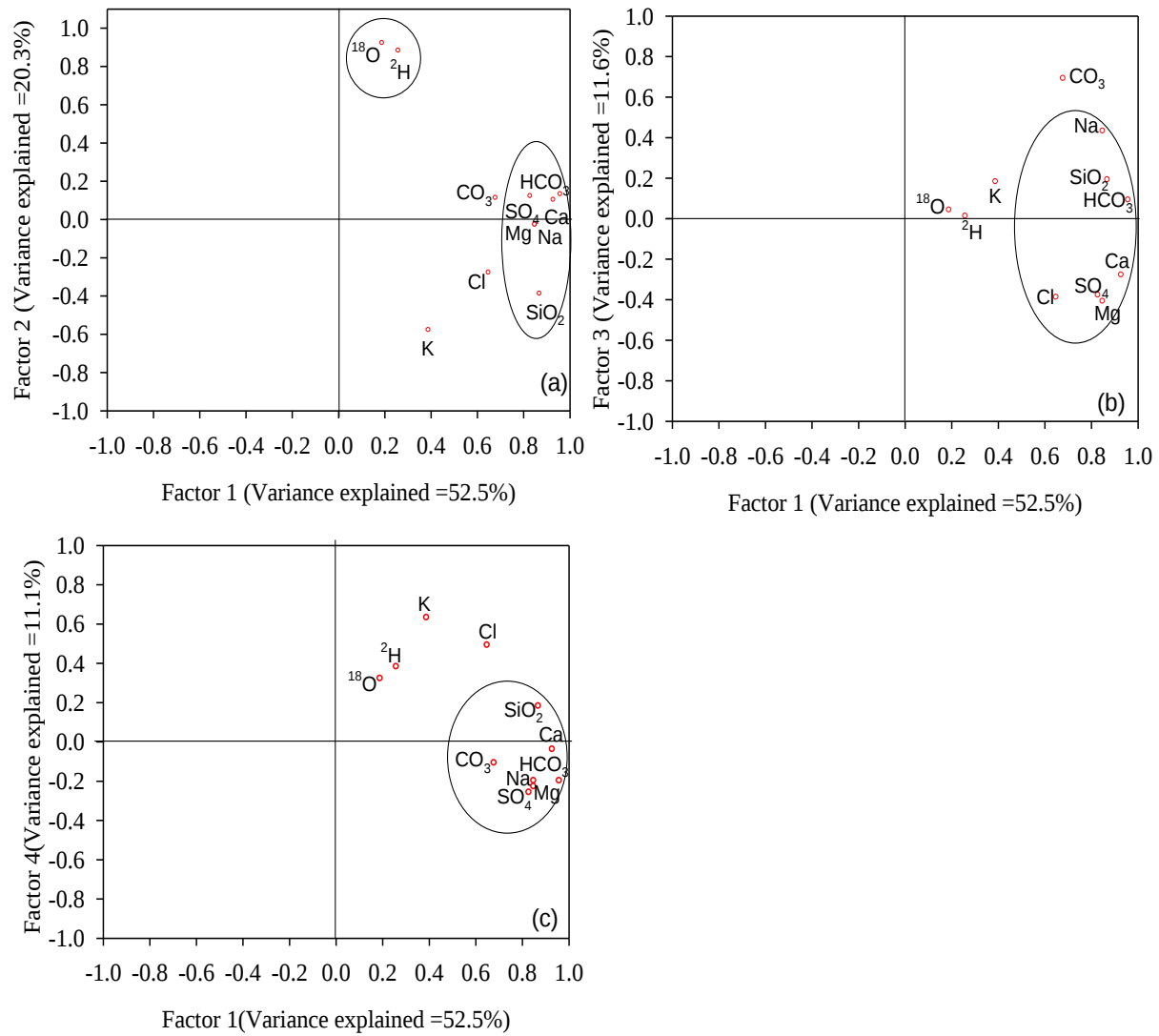


Figure 11: Plot of loadings for Factor 1 and 2 (a), Factor 2 and 3 (b) and Factor 3 and 4 (c)

2.3.9 Hierarchical cluster analysis of water sources

Water sources in Usungu catchment formed three clusters based on their hydrochemical similarity and differences (Fig. 12). The phenon-line drawn on the dendrogram at a linkage distance of 200 marked the linkage distance below which the sources were grouped into the same cluster. The linkage distance between Cluster I and other clusters was elevated (~850). All end-members in Cluster I were wells while Cluster II constituted springs (37.5%) and rivers (62.5%) only. Cluster III constituted rivers, springs and wells (62.5%, 25.0% and 12.5, respectively).

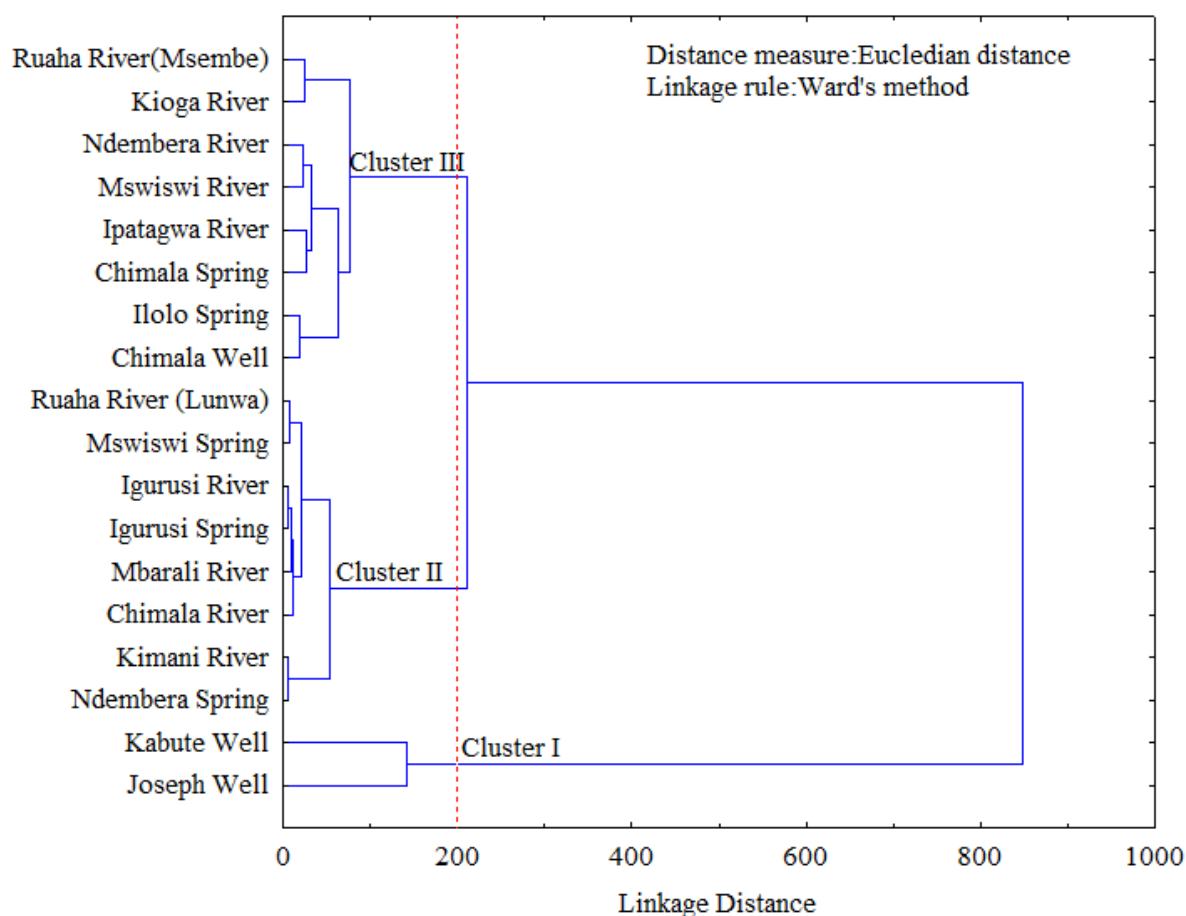


Figure 12: Cluster dendrogram of the samples from the three types of water source

Major dissolved ions and SiO_2 in individual sources in each Cluster in Fig. 12 are shown in Schoeller diagram (Fig. 13a-c), where Na^+ and HCO_3^- were the dominant ions. Similarly, SiO_2 showed high concentrations of more or less than Na^+ and HCO_3^- in all water sources. Generally, the dissolved ions concentration most of water sources were in the order of $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ (mg/l) and $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{CO}_3^{2-}$ (mg/l). Furthermore, Cluster I sources had the highest concentrations of ions than other clusters (Fig. 13a). On the contrary, Cluster II water sources had the lowest ions concentrations. Cluster III water sources had concentrations falling between Clusters I and II (Fig. 13b).

Furthermore, the distribution of the clustered water sources on the $\delta^{18}\text{O}$ - δD plot using their δD and $\delta^{18}\text{O}$ values portrayed no clear distinction between the three clusters (Fig. 14). Water sources from the three sources (rivers, springs and wells) assumed random positions along the LMWL on the $\delta^{18}\text{O}$ - δD scatter plot. Cluster II water sources (62.5% rivers), were slightly

displaced to the right of the LMWL. Also, Fig. 14 showed that water from Kabute Well ($\delta^{18}\text{O} \cong -3.7\text{‰}$ and $\delta\text{D} \cong -21\text{‰}$) fell very close to Ndembera River ($\delta^{18}\text{O} \cong -3.5\text{‰}$ and $\delta\text{D} \cong -20\text{‰}$) along the mixing line. In addition, most of Cluster III end-members and the springs from Cluster II such as Mswisu, Ndembera as well as few rivers namely Mbarali and Ruaha (Lunwa) plotted very close to the LMWL.

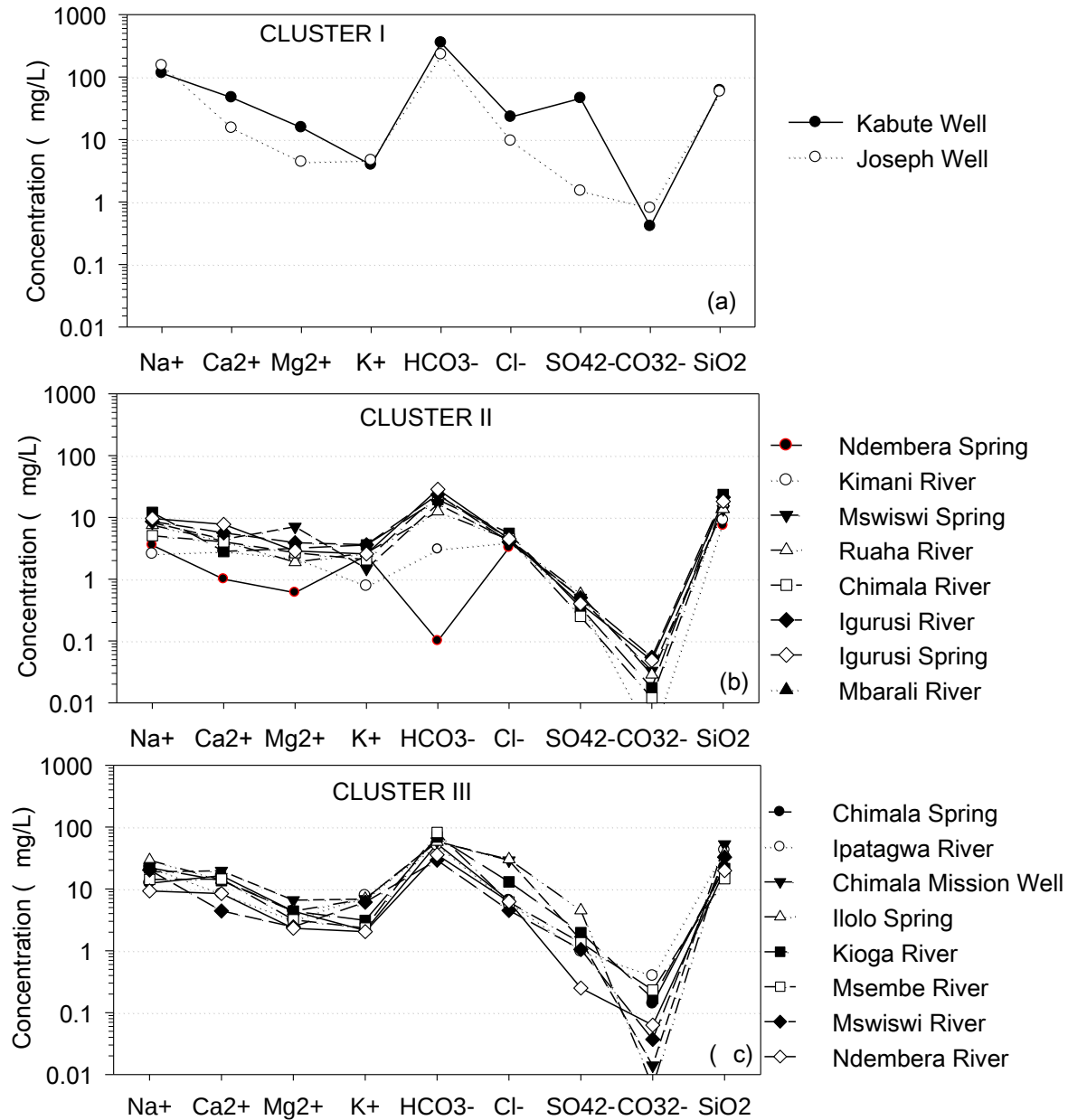


Figure 13: The Schoeller diagram to show the concentration of water sources in the three clusters (Source: After Thyne *et al.*, 2004)

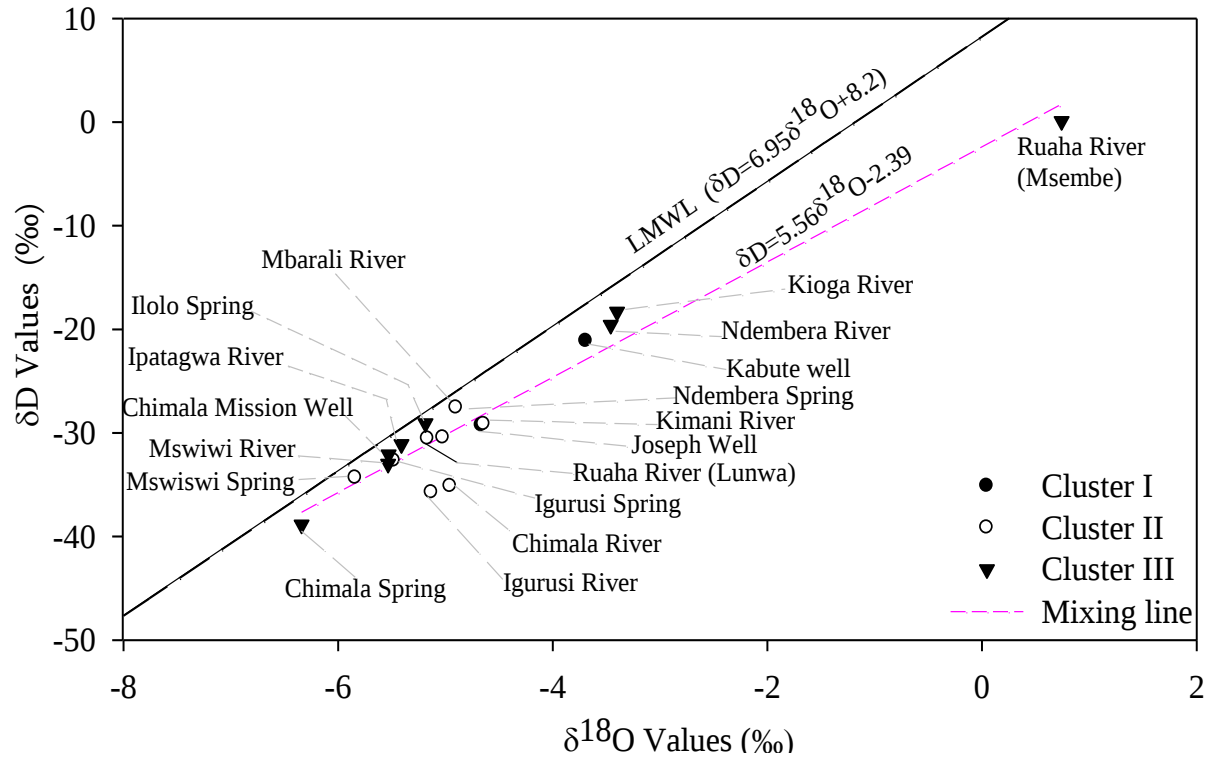


Figure 14: Plot of $\delta^{18}\text{O}$ against δD showing the distribution of end-members of each cluster along the LMWL

2.4. Discussion

2.4.1 Surface-groundwater interaction

The concentrations of the dissolved ions in waters in the order of $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ (mg/l) and $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{CO}_3^{2-}$ (mg/l) (Fig. 13) could be attributed to the abundance of these elements in the source rock minerals as well as their solubility differences (Herojeet *et al.*, 2013; Mangler *et al.*, 2014). They are released in the groundwater through a number of geochemical reactions such as the chemical weathering of minerals, sorption, and desorption, dissolution and precipitation of secondary carbonates and ion exchange between water and clay minerals (Rina *et al.*, 2013). Two natural processes which govern the abundance of hydrochemical facies in water sources in the study area; rock-weathering (22%) and minerals dissolution by rainwater (78%) (Fig. 15). Again, all water sources in Cluster I (Kabute and Joseph wells) plotted under the rock weathering domain (TDS = 100-1000 mg/l), while all Cluster II end-members and 67% in Cluster III (mainly river and springs) plotted under rainfall dominance reactions (TDS = 4-100 mg/l).

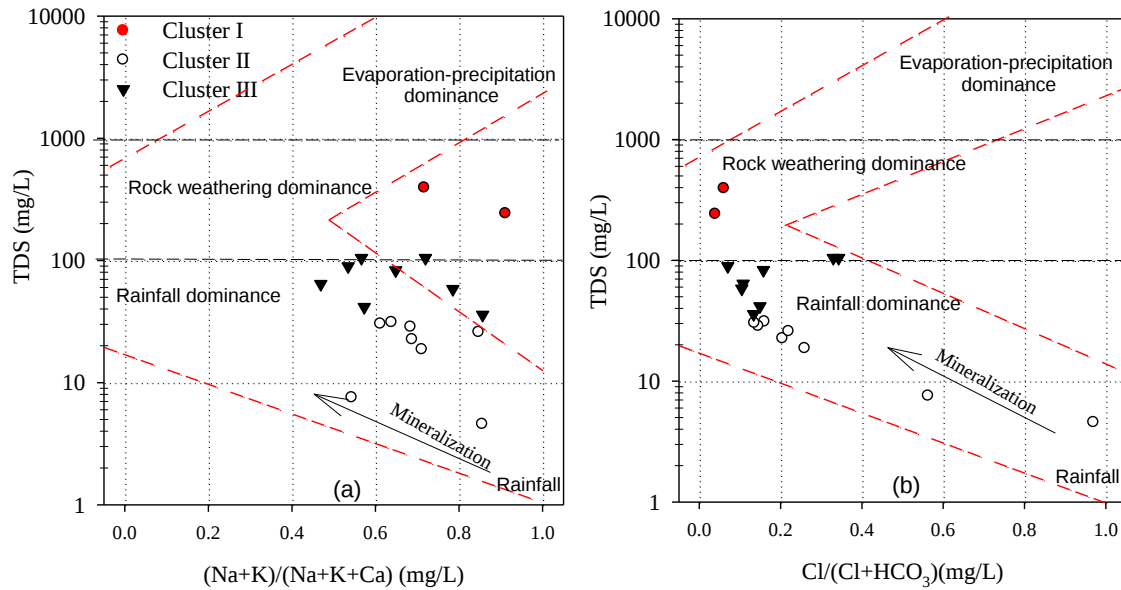


Figure 15: Gibbs diagrams with the samples labeled according to their respective clusters (Source: After Gibbs, 1970)

The rock weathering reactions as well as mineralization reactions in Fig. 15 which influence the abundance of dissolved ions in water are further explained using the ionic ratios in Fig. 16a&b and Fig. 16a-f. High abundance of ions such as Na^+ , Ca^{2+} , HCO_3^- and Cl^- in Usangu catchment water sources could be linked to the presence of highly soluble minerals in the subsurface environment in the study area such as calcite (CaCO_3) and halite (NaCl) as indicated by $\text{Ca}^{2+}/\text{Mg}^{2+}$ and Na^+/Cl^- ratios (Fig. 16a, 15b, and 2.15c). About 27.8% of water sources in Fig. 15a fell between $\text{Ca}^{2+}/\text{Mg}^{2+}$ ratio of 1 and 2, indicating the Calcite dissolution as a main source of Ca^{2+} (Narany *et al.*, 2014). The water sources with this $\text{Ca}^{2+}/\text{Mg}^{2+}$ ratio of 1 and 2 such as Kimani and Igurusi Rivers drain the area with Sandstones and Shale rocks. Igurusi spring is also found on the similar rocks (Fig. 2). Calcite is present in sandstones as the cementing materials or as one of mineral compositions of Shales (Sedimentary rock).

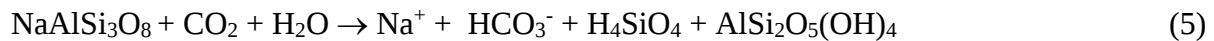
The $\text{Ca}^{2+}/\text{Mg}^{2+}$ ratio >2 in Fig. 16a in about 61.1% of water sources indicate that weathering of silicate minerals is also a source of Ca^{2+} in waters (Narany *et al.*, 2014). Interestingly, the $\text{Ca}^{2+} + \text{Mg}^{2+}$ versus $\text{HCO}_3^- + \text{SO}_4^{2-}$ diagram (Fig. 16d); also supports the weathering of silicates as the source of major dissolved ions; where most of the water sources in all three clusters plotted below the 1:1 aquiline on the Silicate weathering domain. The silicate minerals could most probably be the Epidotes and Synite (Feldspar silicate mineral) which are found in areas around Igurusi Spring. Also, the silicates could be the anorthoclase feldspars in phonolite rocks found in the Rungwe volcanics where Ipatagwa River originates.

Few water sources (11.1%) in Fig. 16a namely Mswisu spring and Chimala river showed dolomite dissolution as a source of Ca^{2+} ($\text{Ca}^{2+}/\text{Mg}^{2+}$ ratio <1). This is justified by the geology of the Chimala river upstream and that of Mswisu spring which constitutes the green Shale rocks with numerous bands of dolomitic limestones ($\text{CaMg}(\text{CO}_3)_2$). Furthermore, those water sources in Cluster II in Fig. 16b which are on the 1:1 indicate that the dissolved ions come from equal intensity of carbonate and silicate weathering processes (Dagar *et al.*, 2016).

Weathering of Silicates such as Albite ($\text{NaAlSi}_3\text{O}_8$) in the terrestrial deposits (laterites) could be responsible for high Na^+ concentrations in Kabute and Joseph Wells (Fig. 16b), where the Na^+/Cl^- ratio was >1 ($\cong 5-16$). According to Narany *et al.* (2014), the Na^+/Cl^- ratio > 1.5 indicate silicate weathering as the source of sodium in water sources. The same author contends that if ion exchange of Na^+ and K^+ in rock materials with the Ca^{2+} and Mg^{2+} in the groundwater is a dominant process, the data on the $\text{Ca}^{2+}/\text{Mg}^{2+}$ versus $\text{HCO}_3^-/\text{SO}_4^{2-}$ tend to shift to the right of 1:1 equiline due to excess $\text{SO}_4^{2-}+\text{HCO}_3^-$. Therefore, Fig. 16e shows that ion exchange between Ca^{2+} and Mg^{2+} in the groundwater with the Na^+ and K^+ in the aquifer material is a most likely source of Na^+ and K^+ in the study area. The ionic exchange reactions between Ca^{2+} and Na^+ is shown in Eq.(4) (Narany *et al.*, 2014).



The dissolution reactions of carbonates (Calcite, marble and dolomites) which are found in the study area rocks such shales, lacustrine beds and limesilicates as well as weathering of silicates, not only contribute to Ca^{2+} and Na^+ , but also may be accountable for the observed higher abundance of HCO_3^- ions in the water sources (Fig. 16a). These two reactions are shown by Eq.(5) (Saravanan *et al.*, 2015) and Eq.(6) (Janardhana Raju *et al.*, 2011). Additionally, the HCO_3^- may also have originated from the dissociation of rainwater weak H_2CO_3 as shown by Eq.(7) (Gupta, 2011).



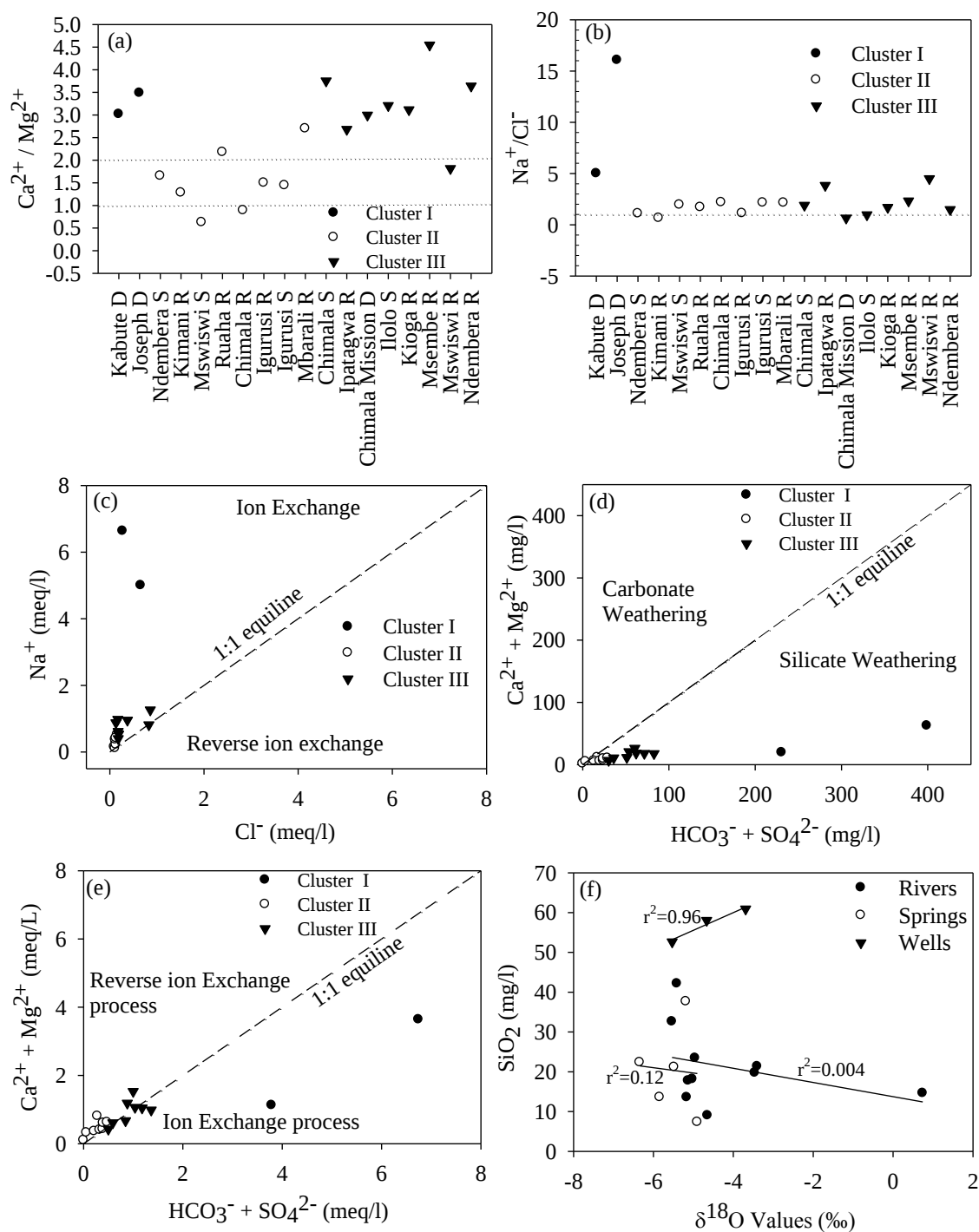


Figure 16: The ionic ratios (a and b), scatter diagrams of different hydrochemical parameters (c-e) and a plot of SiO_2 vs $\delta^{18}\text{O}$ (f)

The $\text{Na}^+ / \text{Cl}^-$ ratio ≤ 1.5 (Fig. 16b) and distribution of most of water sources along the 1:1 equiline on Na^+ versus Cl^- diagram (Fig. 16c) indicates halite dissociation as a major possible source of Cl^- in the water in Cluster II and III end-members. However, Cluster I end-

members in Fig. 16c showed excess Na^+ ; indicating that the Cl^- for balancing this excess must be coming from other sources such as the leaching of easily dissolved Cl-bearing minerals; amphiboles and chloritized biotites. Such minerals occur in granite rocks which are found in the Eastern parts (Ndembera spring-S2), South to Southwest areas around Iloilo Springs (S5) and in the Northwest parts of the catchment (Fig. 2). According to Scott (1987) and Mangler *et al.* (2014), when the Cl^- is leached out, will contribute to the Cl^- ions in the groundwater.

High abundance of SiO_2 in the water sources in Usangu catchment as shown in Schoeller diagram (Fig. 13a-c) could owe to the shales and quartzite rocks (clay and silica rich minerals) which are widely distributed in the North to North-east (Fig. 2). Similarly, the clay and silica rich minerals are found in sandstones rocks that extend from Poroto Mountains extending northwards along Kimani and Ruaha River and areas around Igurusi. The weathering of such minerals may account for high SiO_2 in the water sources (Gupta, 2011). In addition, weathering of rocks rich in silicates and K^+ such as gneiss (biotite gneiss) contribute to both high SiO_2 and K^+ in the subsurface waters.

High concentration of SO_4^{2-} in water from wells relative to springs and rivers (Fig. 6c) may originate from the weathering of different SO_4^{2-} bearing rock minerals in deep subsurface environment, mainly pyrites (Younger, 2009; Janardhana Raju *et al.*, 2011). This argument is supported by the geology of Usangu catchment, whereby the sandstones, quartzites and shales are dominant in the areas around Kimani, Ruaha and Igurusi Rivers (Fig. 2). The quartz in shales in Usangu catchment contains relics of iron sulphide (pyrites). Under oxidative weathering, will contribute to the high concentration of SO_4^{2-} based on Eq.8 (Clark and Fritz, 1997; Janardhana Raju *et al.*, 2011).



Although the dissolution of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) or anhydrite (CaSO_4) was pointed out by Younger (2009) to be among the sources of SO_4^{2-} in the groundwater, it is not likely to be the same for Usangu catchment. This is due to the fact that SO_4^{2-} showed weak correlation with Ca^{2+} and Mg^{2+} ($r=0.59$ and 0.58 , respectively, $p<0.05$, Table 3).

2.4.2 Predominant facies and origin of groundwater

Similar predominant water types to the ones shown in Fig. 10, except Na-Cl type, were reported previously by Robert (2013) who analyzed the hydrochemistry of water samples from Ihefu wetland and areas around Rujewa, in the same watershed. The hydrochemical facies reflect the response of chemical processes operating within the lithological framework and also the pattern of the water, and hence, they describe groundwater masses within an aquifer that differ in their chemical composition (Dano, 2010). The source aquifer rocks from which groundwater originate in Usangu catchment are shown in Table 5. Since the determination of aquifer depths and types was not carried out in this study, this information is supplemented by findings of previous works such as that of Younger (2009) and Ghesquière *et al.* (2015). Worthy mentioning, Table 5 shows that the water sources with Na-HCO₃ and Ca-Na-HCO₃ as predominant facies are originating from the subsurface environment where ionic exchange is prevailing. Excess Na⁺ in Cluster I end-members due to ionic exchange observed in Fig. 16c supports the prevalence of Na-HCO₃ and Ca-Na-HCO₃ as predominant facies in the groundwater.

Table 5: Water sources and their possible origin in the Usangu catchment

Water source	Hydrochemical facies	Cluster	Source aquifer characteristics
Kabute Well	Ca-Na-HCO ₃	I	*Lateritic aquifer rocks with calcite as cementing materials and andesite. Mixed Ca-HCO ₃ and Na-HCO ₃ waters, possibly interconnected granular and bedrock aquifers (Ghesquière <i>et al.</i> , 2015)
Joseph Well	Na-HCO ₃	I	*Lateritic aquifer rocks with calcite as cementing materials and albite. Shallower portions of regionally confined aquifers; waters deduced to have been affected by ion exchange (Younger, 2009)
Ndember a spring	Na-Cl	II	*Granite aquifer rock rich in chloritized biotites, amphiboles and Na ⁺ rich feldspars
Igurusi spring	Ca-HCO ₃	II	*Aquifer rocks with variety of rocks such as shales rich in calcites, limestones, gabbro, norite and hyperites
Mswisu spring		II	Shallow, fresh groundwater in recharge areas in a wide range of aquifer types (Younger, 2009)
Chimala Spring		III	
Chimala Mission Well	Ca-HCO ₃ / Ca-Mg-Cl	III	*A mixture of water from granite rock with chloritized biotites, amphiboles, dolomitic limestones and Na ⁺ and Ca ²⁺ rich Feldspars Mixture of water from shallow, fresh groundwater in recharge areas in a wide range of aquifer types (Younger, 2009)
Ilolo Spring	Na-Cl/ Ca-Na-HCO ₃	III	*A mixture of water from granite rock with chloritized biotites, amphiboles and Na ⁺ and Ca ²⁺ rich Feldspars

*Information extracted from study area Geological map

2.4.3 δD and $\delta^{18}O$ variations in relation to surface-groundwater interconnection

The mean δ -values of $\delta^{18}O$ and δD isotopes in rain waters $-4.2 \pm 2.6\text{‰}$ and $-27.7 \pm 21.6\text{‰}$, respectively (Fig. 7a&b) are less than the mean of the GNIP isotope data values reported by Schotterer (1996). According to this author, the stable isotopes values for Dar es Salaam and Morogoro averaged -2.6‰ and -7.2‰ ($\delta^{18}O$) and -2.8‰ and -11.6‰ (δD), respectively. This East to West continuous diminishing of heavier isotopes from rain water is most likely attributed to continental effect (Geyh *et al.*, 2008).

The slight enrichment of river waters with heavier $\delta^{18}O$ and δD isotopes than groundwater and rainwater sources (Fig. 7) is probably the impact of evaporation-induced isotopic enrichment of surface water (Mckenzie *et al.*, 2010; Ghiglieri *et al.*, 2012). The comparison

of isotopes values of springs and wells in Fig. 8c-d and Fig. 8d-f, shows that water from wells are more enriched relative to springs. One of the reasons could be the long flow pathway from recharge area in the Kipengere and Poroto highlands to the low elevation areas. According to Ayenew *et al.* (2008), enrichment in heavy isotopes in groundwater tends to increase as it flows from highlands to low lands. The relative elongated water-rock minerals interaction along the flow path allows the exchange of ^{18}O isotope between groundwater molecules and silicate minerals to take place as shown in Eq.9 (Clark and Fritz, 1997; Geyh *et al.*, 2008).



Another possible reason could be the recharge of groundwater with isotopically enriched river waters. This argument is evidenced in Fig. 16 where Kabute well and Ndembera river plotted so close along the mixing line. Furthermore, in Fig. 9d-f it is shown that the $\delta^{18}\text{O}$ isotopic composition of water samples from Kabute well in June and November was about -3.8‰ and -3.6‰, respectively. These values were closely related to those of Ndembera river for the same sampling period (-3.5‰ and -3.3‰ for June and November, respectively). The results suggest that river loses water to the groundwater aquifer during the dry season. The geological formation in the Ndembera area is of terrestrial alluvial deposits, mainly residual clay and sand soils, laterites and cement which possibly could allow ease seepage of water from the river bed to the groundwater (see Fig. 2).

The bivariate plot $\delta^{18}\text{O}$ and SiO_2 (Fig. 16f) shows that despite the overall weak and negative correlation between SiO_2 and $\delta^{18}\text{O}$ ($r = -0.13$, Table 3), the SiO_2 in waters from wells have a positive linear relationship with $\delta^{18}\text{O}$. Since SiO_2 in the groundwater is a result of weathering of silicate minerals after a considerable time of water-rock contact, it can be argued that the formation of SiO_2 has a positive relationship with $\delta^{18}\text{O}$ enrichment due to ^{18}O isotope exchange taking place along silicate weathering in the deep aquifer (Eq.9). On the contrary, the SiO_2 concentrations decreased with increasing isotopic enrichment in rivers and springs. This could be a result of either active uptake of SiO_2 by plants and algae in streams springs (Baskaran, 2011).

The isotopes enrichment trend of November > February > June > April in rivers observed in Fig. 8g-h could be explained from different perspectives. Firstly, the highest enrichment of rivers water in November could be the induced evaporation towards the end of the dry season which is displayed along the evaporation line (Fig. 9). Secondly, it could be the release of isotopically enriched baseflow water into the rivers during dry months (July-November). The delayed baseflow is isotopically enriched through $\delta^{18}\text{O}$ exchange with rock minerals (Clark and Fritz, 1997). Furthermore, the observed trend could also be attributed to the continuous dilution of pre-event baseflow by isotopically depleted rainwater which enters the rivers directly or as the surface runoff.

Extremely low seasonal variation of $\delta^{18}\text{O}$ and δD isotopes in groundwater sources observed in Fig. 8c-f could be interpreted as the result of fairly well mixing of the whole annual rain water which recharges the groundwater (Darling *et al.*, 2006). Nevertheless, results in Table 1 showed neither the sources nor season had significant effects on $\delta^{18}\text{O}$ and δD isotopes concentration. These groundwater sources plotted very close to the LMWL than the river waters in Fig. 9, indicating to have been slightly affected by evaporation (Katz, 1998). The results may also indicate a recharge of the surface and groundwater from the common source, which is the meteoric water (Ayenew *et al.*, 2008).

2.4.4 Hydrological connections and flow pathways

The significant variations of hydrochemical parameters' concentrations among water sources (Table 1, $p < 0.05$) indicate that the hydrochemistry of water in the catchment is the function of a type of water source itself. The variations could be attributed to various factors which determine the end-signature of water chemistry of a water source such as the type of geological formation it flows through (Scott, 1987; Mangler *et al.*, 2014) and the type of dominant weathering and ionic exchange reactions that is taking place in the subsurface environment (Narany *et al.*, 2014). The Silicate weathering and isotopic fractionation have been shown by Factor analysis results in Fig. 11 to be the two main factors which contribute major variations of water sources in Usangu catchment. Factor 1 which showed highly positive loading of Ca^{2+} , Mg^{2+} , Na^+ , SO_4^{2-} , HCO_3^- and SiO_2 suggests to be associated with carbonates and silicates weathering (Saravanan *et al.*, 2015). Factor 2 could be defined as stable isotopes fractionation because of high positive loadings of the stable isotopes of water ($\delta^{18}\text{O}$ and δD). These significant variations in water hydrochemistry are useful in

characterizing the hydrogeology of a watershed (Thyne *et al.*, 2004) and the hydrological interactions among water sources as well as their flow pathways (Ayenew *et al.*, 2008).

The lack of significant mean differences of hydrochemistry parameters of waters from rivers and springs as well as the existence of a significant difference between wells and other sources at 95% confidence level (Table 2) imply a closer hydrological interconnection between rivers and springs. The results agree with the argument by Darling *et al.* (2006), that there are equally rare cases where spring waters contributing to streams and rivers may have been isotopically modified in the subsurface. Again, the close similarity between springs and rivers in this study is backed by the co-existence of springs and rivers in Cluster II and III (Fig. 12), as well as their distribution on the same rainfall domain on the Gibbs diagram (Fig. 15). The observed close relationship between springs and rivers and differences between wells and other water sources may be attributed to the main natural mechanisms controlling the minerals dissolution and weathering when the infiltrating water is moving through different subsurface pathways (Gibbs, 1970; Winter, 1998; Kazemi *et al.*, 2012; Saravanan *et al.*, 2015).

Subsurface rock weathering and dissolution of minerals by rainwater are identified in the study area as the main natural mechanisms which govern the amount of dissolved constituents in the groundwater (Fig. 15). In addition, the amount of dissolved materials resulting from these two mechanisms is owed to the duration of rock-water contact (Baskaran, 2011; Li *et al.*, 2014). According to Winter (1998), longer contact time between water and subsurface materials in deeper flow systems, which normally have longer flow pathway, will result to waters with higher amounts of dissolved chemicals.

The rock-water interaction and associated processes, the flow patterns and the hydrological connections between surface and subsurface water in the study area are conceptualized on the hypothetical diagram (Fig. 17). The diagram shows that when it rains in the main recharge area (A) which represents Kipengere and Poroto Mountains, the water partitions into a surface runoff that goes into the rivers and other portion infiltrates into the soil. Some water from the soil may immediately return to streams (B) after few days or weeks (quick flow pathway). The chemistry of water in the flow path A-B will be insignificantly affected by dissolved minerals (Winter, 1998). Alternatively, the water that flows through pathway A-C,

may take few weeks and months to return to the streams as the springs (Winter, 1998). This short time of water flow in the shallow depth aquifers implies a short period of rock-water interactions. The implication is the low TDS values for springs and rivers in Cluster II end-members as observed on Gibbs diagram (Fig. 15). From the work of other authors (Winter, 1998; Sophocleous, 2002), the flow path A-B and A-C could be referred to as local and quick flow pathway. The waters in sources that emanate from this kind of flow pathway are often of a recently infiltrated rainfall (Ghesquière *et al.*, 2015), which was also found to be the most important source of surface water flows in Makanya catchment, Tanzania (Mul *et al.*, 2007).

The water that flows through path A-L and ultimately comes out as springs, but flow path A-D which takes relatively a bit longer flow path than A-B and AC comes out as the baseflow. Consequently, water originating from such flow pathway is thought to have dissolved a moderate amount of aquifer rock minerals, moderately exchanged the ions with the rock minerals and carry out the weathered materials. The implication could be the existence of moderate concentrations of hydrochemicals, expressed as TDS in the Cluster III end-members (Fig. 15).

The presence of fault line systems in the study area as shown in Fig. 2 are presented in Fig. 17 as “Fr”. These faults provide the aquifer–river hydraulic link, which is one possible way in which groundwater mixes with water in rivers. According to Ayenew (2003) the mixing of groundwater and water in rivers in the fractured rift is very common. The presence of faults could be linked with observed relatively high concentration of ions in some rivers (Mswisu and Ipatagwa, Fig. 13c). These water sources also demonstrated Ca-Na-HCO₃ water type similar to deep groundwater source, Kabute well (Fig. 10), which has been shown by Ghesquière *et al.* (2015) could be interconnected to granular and bedrock aquifers.

The water found in wells could most likely follow the flow path A-F-H-I through G. This point G could be the faults which preferentially permits pathways for groundwater flow (Younger, 2009). This path can be both local or a regional flow system (Sophocleous, 2002). The water flow through this flow path may take a long time up to centuries (Younger, 2009) or even millennia (Winter, 1998; Dagar *et al.*, 2016). This longer time of water-rock interaction results into high concentrations of dissolved ions in the groundwater (Freeze and

Cherry, 1979; Kazemi *et al.*, 2012). The implications of the elongated flow time in the path A-F-H-I is the elevated TDS values for Cluster I end-members ($>100\text{mg/l}$ - $<1000\text{mg/l}$, Fig. 15). Generally, the TDS in groundwater increases along the groundwater flow path from high to low elevations due to progressive mineral dissolution (Li *et al.*, 2014). This argument is supported by the high TDS in wells in the low elevations and low TDS in most of the springs in the higher elevations (Fig. 18). Generally, the TDS in water sources increase with decreasing altitude, but the correlation is rather very small ($r = 0.13$). This could be attributed by low TDS in rivers which were sampled in the low altitudes (800 -1200 m.a.s.l) as shown in Fig. 18.

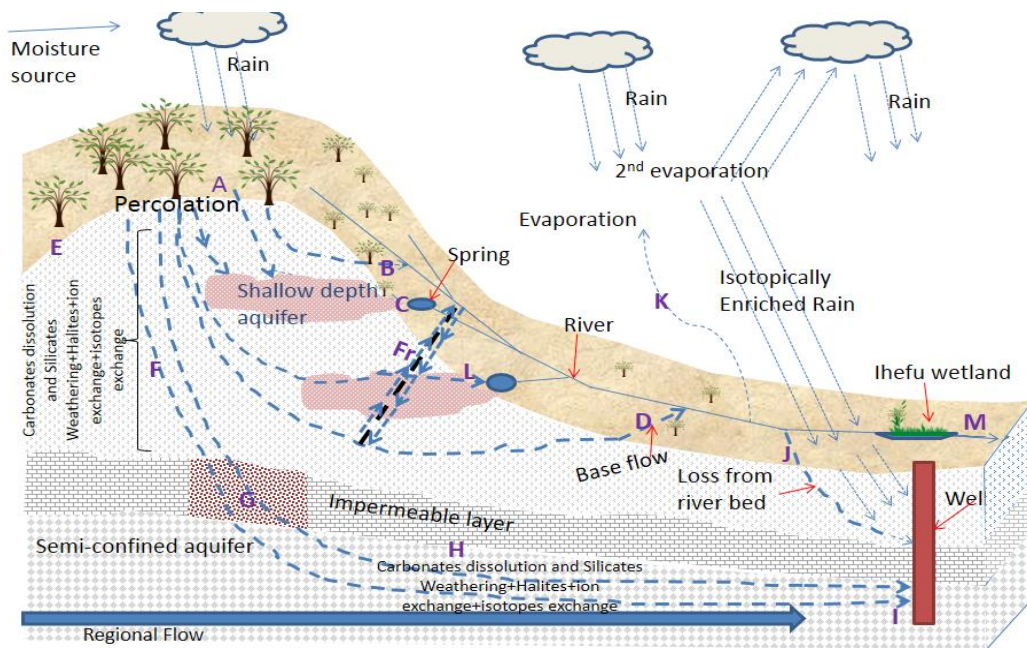


Figure 17: Conceptual diagram of Usangu catchment major hydrological processes, water sources, and chemical reactions governing hydrochemistry

The higher concentration of heavier isotopes in the waters from wells relative to springs in Fig. 7a&b could also be associated with the longer flow path from higher altitudes to low altitudes as it is the case for TDS (Fig. 18). It is evident that springs are found in higher elevation than wells ($\sim 1200\text{-}2000$ m.a.s.l, Fig. 8c-d versus $\sim 1170\text{-}1080$ m.a.s.l, Fig. 8e-f, respectively). The increasing enrichment of δD and $\delta^{18}\text{O}$ with increasing distance from high elevations to low elevations has also been reported in Ethiopia by Ayenew *et al.* (2008). In this study, this trend is associated with the exchange of ^{18}O isotope between groundwater molecules and silicate minerals (Eq.9) which takes place along the flow path A-F-G-H-I (Fig. 17).

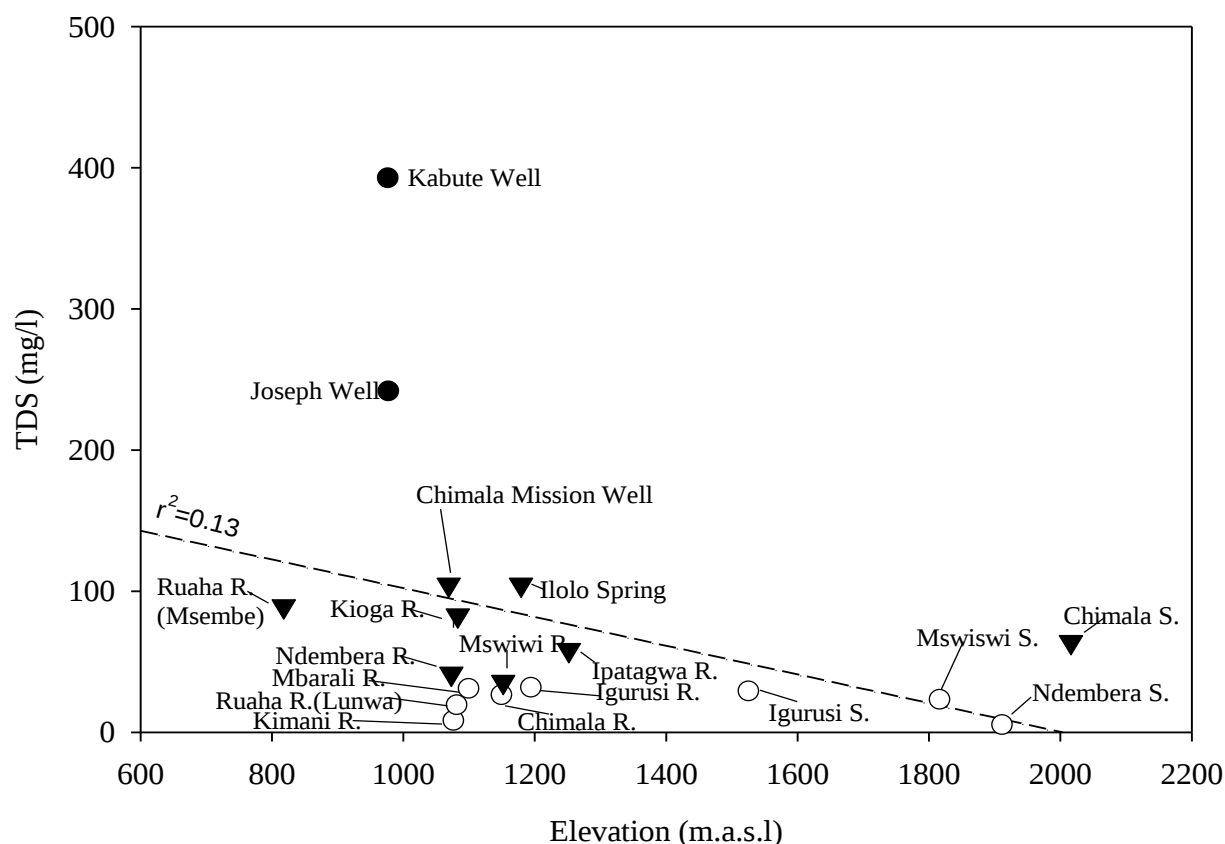


Figure 18: Elevation versus mean TDS values in water sources

Three types of isotopic fractionation mechanisms are possibly happening in the study area that are depicted on the hypothetical diagram (Fig. 17). The first one is the fractionation due to isotopic exchange that occurs along the groundwater flow path (A-F-G-H-I). The second is due to surface evaporation induced isotopic enrichment of water in rivers (K). This occurs when water is flowing from high to low altitudes to Ihefu wetland and Great Ruaha River at Msembe (M). The third one is the secondary evaporation of rainwater during the months with little rains or atmosphere is not saturated with moisture. Furthermore, Fig. 17 show different ways in which the mixing water of different isotopic signatures occur. For example, the isotopically enriched rain mixes with surface water (Rivers) during rain events. The same rainfall which falls on the land surface may infiltrate the soils and recharge the subsurface water (J-I). Again, the mixing of groundwater and surface water occurs at D as the baseflow enters the rivers.

2.4.5 Factors influencing variations in $\delta^{18}\text{O}$ and δD concentrations in rainwaters

The relatively depleted values of $\delta^{18}\text{O}$ and δD in February rainwaters than April (Except Mswisu) observed in Fig. 8a-b is contrary to the findings from the previous study (Freeze and

Cherry, 1979). According to Freeze and Cherry (1979), as rainfall season proceeds, the heavy $\delta^{18}\text{O}$ and δD will drop out first, and as a process of condensation and precipitation is repeated many times, the subsequent rains become depleted in $\delta^{18}\text{O}$ and δD . Nevertheless, the general trend of isotope enrichment in rainwaters in Usangu catchment in April (Fig. 8-a-b) when there is less rainfall (Fig. 19), agreed with the findings by Scholl *et al.* (2009) who analyzed the data from tropical stations in the GNIP network. Higher values of δD and $\delta^{18}\text{O}$ were observed during months with less rainfall, and lower values of δD and $\delta^{18}\text{O}$ correlated with higher precipitation amounts. This could be attributed to amount effect (Dansgaard, 1964) which often results to high values of δD and $\delta^{18}\text{O}$ in the rainwater that is reaching the ground due to high evaporation of the light raindrops during the light rains when the air is less saturated with moisture.

Moisture source could also be attributed to the variations of isotopic composition in rainwaters in Usangu catchment. Heavy rains occur in the study area in December-February as shown in Fig. 19, during the time which the Inter-Tropical Convergence Zone (ITCZ) is in the extreme continental southward location between Tanzania and central Mozambique (Mbululo and Nyihirani, 2012). During this time the atmosphere is warm and saturated with moisture. The occurrence of secondary evaporation of falling rain drops to cause isotopic fractionation is unlikely. In the beginning of April, the ITCZ moves northward, and the Southern highlands receives less moisture from the cool South Easterly winds. This less moist air could be the reason for enriched δD and $\delta^{18}\text{O}$ values in April rainwater.

The unique isotopic concentration trend Feb>April observed in Mswisu rainwater (Fig. 8a-b) could be just a matter of chance that the sampling of rainwater took place on the day with light rain (14th February < 18th April, Fig. 20). According to Scholl *et al.*, (2009) the values of δD and $\delta^{18}\text{O}$ in rainwater are higher during the time of low rainfall. This could cause the re-evaporation of rain drops and leads to isotopically enriched rain to reach the ground. This enrichment of $\delta^{18}\text{O}$ in rainwater in February for Chimala and Mswisu rainwaters (Fig. 8a) and right displacement of Rujewa and Chimala rainwaters from the LMWL (Fig. 9) could be attributed to amount effect that is reflected in the deuterium excess (d-excess) values (Fig. 21). According to Gat *et al.* (2001) the enrichment of $\delta^{18}\text{O}$ in rainwater due to amount effects also results small to negative deuterium excess values.

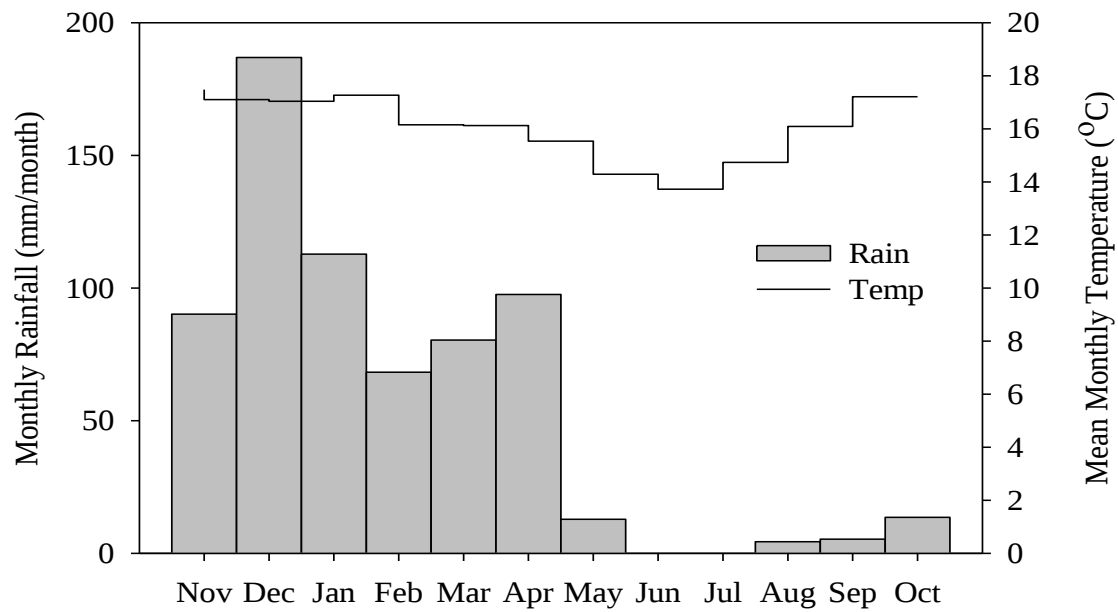


Figure 19: Mean monthly temperature and monthly precipitation trend for Matamba weather station (Data arranged according to Usangu Catchment Hydrological year (Data Source: RBWB, 2014)

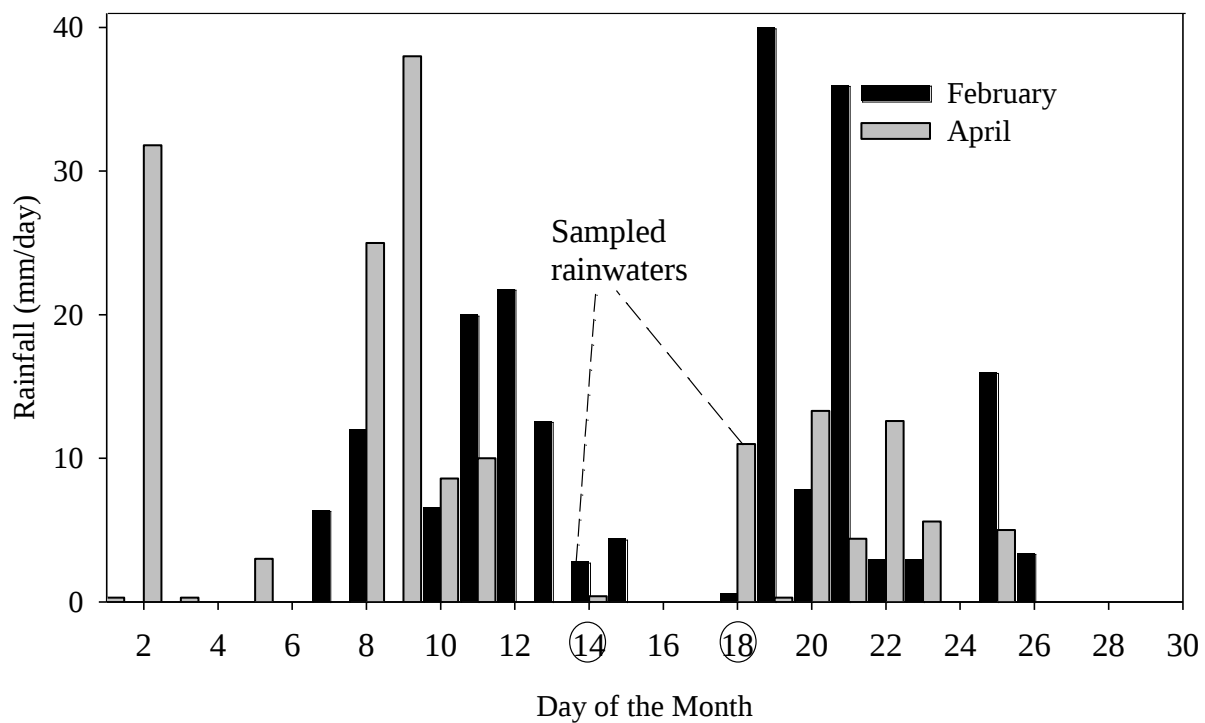


Figure 20: Daily precipitation records for February and April at Matamba weather station (Circled dates are the sampling dates (Data Source: RBWB, 2014)

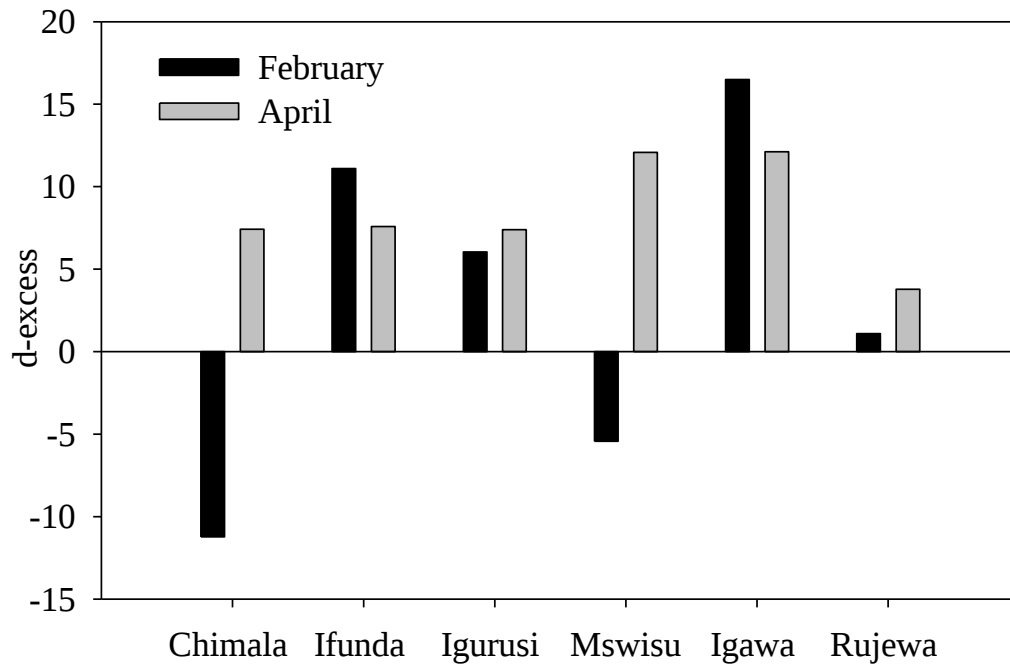


Figure 21: Deuterium excess values of rainwaters in Usangu catchment

2.5. Conclusions

Water hydrochemistry variations have been successfully used in characterizing and describing the hydrological processes in Usangu catchment such as the origin of waters; flow pathways and hydrological connection among surface and subsurface water sources. The origin of waters in rivers, springs and wells in the study area have been found to be from the local and recent meteoric water. The study area has two main subsurface flow pathways; i) a shallow aquifer flow pathway, a relatively short and fast flow system which connect springs and rivers. The dissolved ions in this pathway are mainly controlled by the dissolution of minerals in the soil and shallow depth aquifers by rainwater ii) a slow and deeper aquifer flow pathway, which its dissolved ions is influenced mainly by water-rock interaction in the subsurface environment.

The existence of two main flow systems in the Usangu catchment suggests that management and development of surface and subsurface water resources need different approaches. For example, to protect the local and short pathway that connect rivers and springs could need the protection of forest cover by Usangu catchment stakeholders in the elevations above 1600 m.a.s.l where most of the recharge of groundwater occurs. Most of the springs are also found

in the areas above this elevation, whereby, a decrease in the forest covers will reduce the recharge and hence adversely affect the springs-rivers flow system.

The study identified the isotopic exchange between groundwater and aquifer matrix to be one of the possible isotopes fractionation mechanism in groundwater while the temperature induced evaporation leads to isotopic enrichment of surface waters (rivers). These modifications of isotope signatures have enabled the identification of watershed hydrological processes such as mixing of subsurface baseflow with surface water, recharge of groundwater by rivers in the lower elevations in the alluvial formations, and possible flow pathways of waters in the surface and subsurface water sources.

Rainfall was only analyzed for stable isotopes compositions. The study recommends future studies to analyze the dissolved ions in rainfall such as Cl^- , HCO_3^- and SO_4^{2-} . This is in order to ascertain the actual amount of dissolved ions emanating from the water-soil and water-rock interactions. In addition, the influence of regional flow as a source of water in the deep aquifer systems was beyond the scope of this study. However, it is recommended that the hydrologists take the opportunity to use tracers and extend the study beyond the Usangu catchment boundaries to investigate the existing regional and inter-catchment hydrological connections for effective management plans of this catchment. The flow direction of waters in this study was deduced from concentration of dissolved ions-elevation relationship without the knowledge of aquifer physical characteristics such as aquifer depths. Thus, geophysical surveys to map aquifer types and exactly depth of aquifers in the catchment are recommended to gain more knowledge on water resources for proper water resources use planning and protection.

CHAPTER THREE

A Markovian and cellular automata land-use change predictive model of the Usangu Catchment¹

Abstract

Usangu catchment located in Southern Tanzania, produces more than 30% of rice produced in the country. Given the role of this catchment, proper management of land and water is important for sustainability of agricultural production. The level of required management depends on the understanding of future land use/cover changes that affect both agricultural land sizes and water balance of the catchment. Thus, the objective of the study was to simulate the 2020 land use and cover of the catchment based on the 2000, 2006 and 2013 land use and covers using Markov Chain and Cellular Automata Analysis (CA-Markov) models. During the analysis, the relative importance of land use and cover change factors was determined using the Analytic Hierarchy Process (AHP) and aggregated using Weighted Linear Combination (WLC) under Multi-Criteria Evaluation (MCE) approach. The standard kappa coefficient (κ -standard) and overall agreements of the model were 0.6776 and 0.9125 respectively. The error due to quantity was 0.0243 while error due to allocation was 0.0667. The simulated land use/cover 2020 scenario shows the increase in urban area by 8.2% and a major decrease in forestland and shrubs by 20.6% and 6.9% respectively. About 19.6% grassland and 8.5% of agricultural land in 2013 will be converted to urban land by 2020, suggesting increase in pressure on food security if new technologies of producing more on the same are not adopted. On the other hand, about 372.0 km² (10.4%) of wetlands and 368.2 km² (10.3%) of woodlands will be converted to agricultural land, resulting into loss of ecological functions of a wetland and undesired changes in water balance of the catchment such as increased evapotranspiration, surface runoff and reduced infiltration. The 2020 land use and cover simulation model of Usangu catchment used in this study provide some useful information for determining future land use and cover scenarios. In addition, it provides data for water balance models and preparation of future ecological conservation plans.

Keywords: Markov chain, Cellular automata, Land use change, Modelling, Prediction, Usangu

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3.1 Introduction

The land use and cover change is a major driver of global change, including the change of ecosystem processes, biological cycles and biodiversity (Behera *et al.*, 2012). Land use and cover change has been accelerating as a result of socio-economic and biophysical drivers (Lambin *et al.*, 2001). The changes are closely linked with the sustainability of socio-economic development since they affect essential parts of the natural capital such as vegetation, water resources and biodiversity (Behera *et al.*, 2012), and human life (Islam and Ahmed, 2011). Therefore, the quantification of the land use and cover changes in terms of space, time and direction is crucial for sustainability of ecosystem and socio-economic development.

Due to the enormous impacts and implications generated from the land use and cover changes, the International Human Dimension Program (IHDP) commends the necessity of improved understanding, modelling and projection of land dynamics from global to regional scale and focusing particularly on the spatial explicitness of the processes and outcomes (Geoghegan *et al.*, 2001; Islam and Ahmed, 2011). Different researchers have recently addressed land use change issues to better understand the causes and consequences of land use change (Verburg *et al.*, 2004; Kashaigili *et al.*, 2006a; Verburg *et al.*, 2006; Koomen and Stillwell, 2007). The aspects of extent and location of future land use changes as the methods for evaluation and advancing the land use and cover changes have also been worked by various researchers such as Pontius (2002), Pontius *et al.* (2004) and Brown *et al.* (2013).

Watersheds, by nature, are dynamic systems; therefore, they are in a constant state of change (McCuen, 1989). The land use and cover changes in the watershed result in the changes in the performance characteristics of the watershed (water balance components) including water infiltration rate, runoff and base flow (Zhang *et al.*, 2002; Zhang and Schilling, 2006; Mulungu and Kashaigili, 2012). The identification of the driving forces responsible for these changes is needed for projecting future land cover trajectories (Giri *et al.*, 2003). In order to understand and be able to model the process of land use and cover change, and predict the future fate of the land use and cover in a certain watershed, land use and cover change models are inevitable. These models enable the analysis and modelling of land use and cover dynamics in a hydrological unit of a watershed, which is important as it helps us to understand its totality (Behera *et al.*, 2012).

Land use change models are tools to support the analysis of the causes and consequences of land use changes (Verburg *et al.*, 2004). These models for predicting land cover changes which are classified as mathematical equation based, system dynamic, statistical, expert system, evolutionary, cellular and hybrid models (Katana *et al.*, 2013). However, the most commonly used in recent land use and land cover literature are the cellular and agent-based models or a hybrid of the two (Berger, 2001). The CA-Markov model is a hybrid of the cellular automata and Markov models. The CA-Markov model is suitable for land cover change detection and simulations (López *et al.*, 2001; Behera *et al.*, 2012; Baysal, 2013). This is because they take into account spatial and temporal components of land cover dynamics (Houet and Hubert-Moy, 2006).

The use of CA-Markov model in the land use and cover change studies, compared to other models for the similar task, has its advantage and limitations. In terms of advantage, CA-Markov model has high efficiency, simple to calibrate and high ability to simulate multiple land covers and complex patterns (Eastman, 2003; Memarian *et al.*, 2012). It enables a more comprehensive simulation as compared to other land use and cover change models such as a GEOMOD and Conversion of Land Use and Its Effects at Small regional extent (CLUE-S) (Mas *et al.*, 2007). The limitations of the CA-Markov model in land use and cover change predictions include its inability to combine the social, human and economic dynamics in the simulation, which can be realized in agent-based modelling systems (Arsanjani *et al.*, 2011). The CA-Markov model fails to recognize new developments taking place in the area (Memarian *et al.*, 2012), in addition, the socio-economic and urban planning concerns for urban growth are not quantitatively incorporated into the model (Myint and Wang, 2006). Failure to incorporate the new development plans leads to the decrease of prediction of CA-Markov when it is used to predict for longer periods of time due to the fact that a uniform transition rule is used by the model throughout the simulation period (Samat, 2009).

A Markovian process is one in which the future state of a system can be modelled purely based on the immediately preceding state. Thus, Markov Chain Analysis will describe the land use/cover change from one period to another and use this as the basis to project future changes. This is accomplished by developing a transition probability matrix of land use change from time one to time two, which forms the basis for projecting future scenarios (Eastman, 2012). In Markovian process, the state of a system at time two ($t+1$) can be

predicted by the state of the system at time one ($t=1$) given a matrix of transition probabilities from each cover class to every other cover class (Eastman, 2012). In this study, the 2020 land use/cover was predicted based on the state of 2006 and 2013 land use/cover.

Markovian land use and cover modelling is a time series GIS analysis tool of land cover changes. Advances in remote sensing for change detection and in the incorporation of remotely sensed data and auxiliary data into GIS have made it possible to overcome the limitations of data and computation of land use and cover changes as well as change predictions (Ball, 1994). The integration of satellite remote sensing, GIS, and Markov modelling provides a means of changing the emphasis of land use and land cover change studies from patterns to a process (Weng, 2002). GIS and remotely sensed data provide means to define CA-Markov initial conditions, parameterization of the model, calculations of the transition probabilities and determination of the neighbourhood rules (Wang and Zhang, 2001).

The CA-Markov model is one of the spatial transition-based models. It is one of the most accepted method for modelling land use and cover change using the current trends because it uses evolution from “ $t-1$ ” to “ t ” to project probabilities of land use and cover changes for the future date “ $t+1$ ” (Houet and Hubert-Moy, 2006; Behera *et al.*, 2012; Eastman, 2012). The model is based on probability that a given piece of land will change from one mutually exclusive state to another (Houet and Hubert-Moy, 2006). These probabilities are generated from past changes and then applied to predict future change (Behera *et al.*, 2012). CA-Markov model is able to simulate changes in multiple land use types (Houet and Hubert-Moy, 2006), hence giving possibilities of simulating the transition from one category of land use and cover to another (Behera *et al.*, 2012).

The results of this work showed how the land use and cover in Usangu catchment will look like in 2020 based on the past (2000 and 2006) and present (2013) land covers. The simulated 2020 land use and cover data was used as one of the inputs in SWAT model for Usangu catchment water balance analysis. Knowing the state of future land use and cover of the catchment will facilitate water balance analysis.

3.2 Materials and Methods

3.2.1 Study area

Usangu sub-catchment is found in the upper part of Rufiji Basin in Tanzania. Its geographical boundary lies between latitudes $7^{\circ}45'$ - $9^{\circ}25'S$ and longitudes $33^{\circ}40'$ - $35^{\circ}40'E$ (Fig. 22). The catchment is surrounded by the Kipengere and Poroto mountains in the South and Chunya Mountains in the Western side. The drainage area of Usangu catchment covers an area of approximately 20,800 km². About 4,840 km² (23%) of the Usangu sub-catchment is in the alluvial plains below 1100 meters above sea level (m.a.s.l.). The remaining 77% of the catchment area lies in the 'high catchment', which ranges from 1100 to over 2000 meters above sea level (m.a.s.l.). The Usangu catchment is vital to Tanzania for its irrigated rice production as well as for its livelihoods options for smallholder farmers and agro-pastoralists (Shu and Villholth, 2012). The Usangu catchment supports over 30 000 rice-producing households on approximately 115 000 ha of irrigated land, which contributes about 30% of the rice production in Tanzania (WB, 2017).

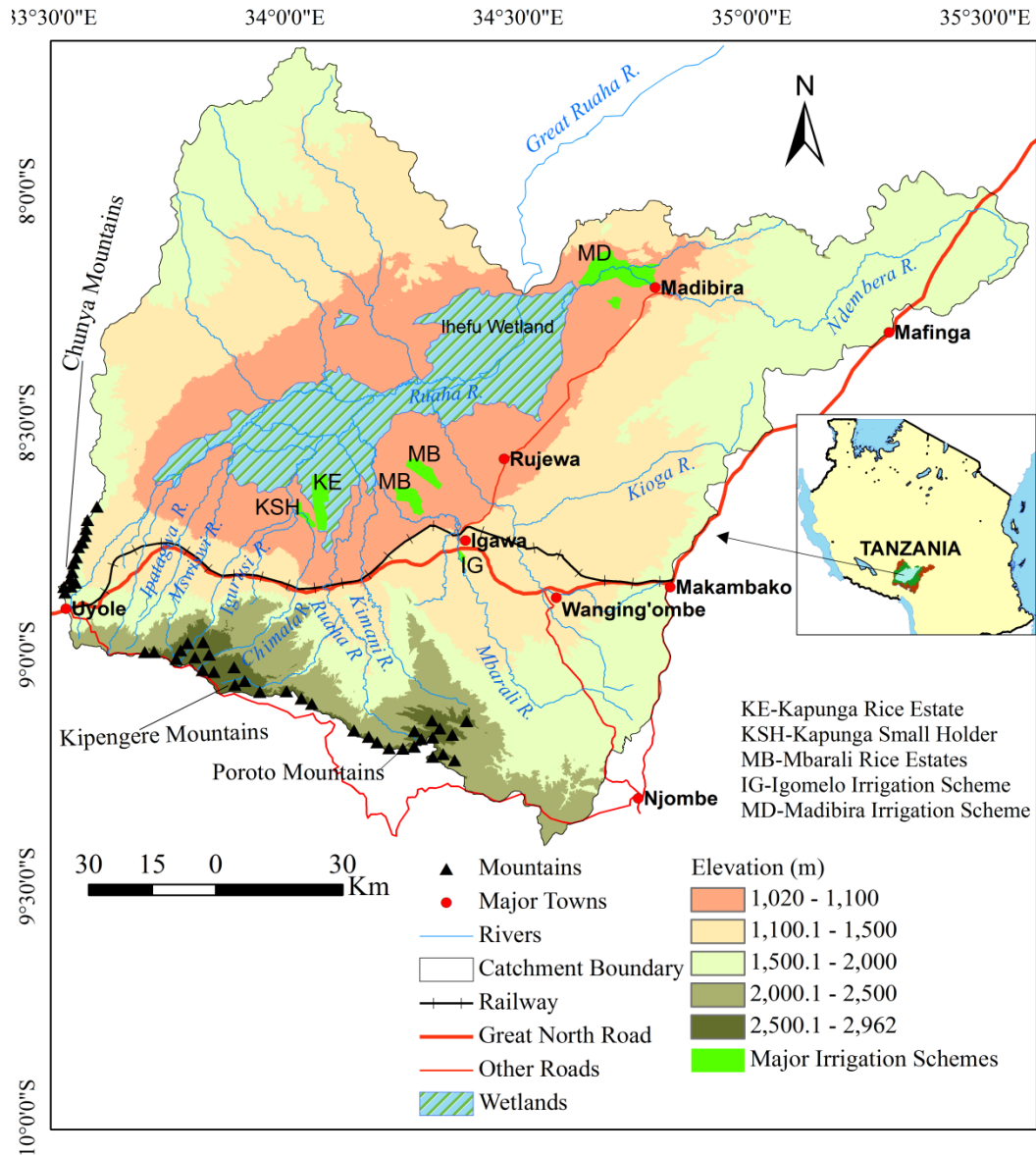


Figure 22: Map of the study area

3.2.2 Land use/cover data sources and classification

Historical land use/cover classified image maps for Usangu Catchment were obtained by classifying Landsat satellite images of 2000, 2006 and 2013. These images were classified using ERDAS Imagine 11 and ArcGIS Desktop v.10.0. Satellite imagery for land use/cover analysis was acquired through direct download from the U.S. Geological Survey website (<http://glovis.usgs.gov>). Usangu Catchment extends over three different Landsat paths and rows. The dates of the satellite imagery used in the study and their associated path and rows are shown in Table 6. The spatial resolution of these satellite images 30 meters. The images were purposely selected from the US Geological Survey website, based on the growing

calendar in such a way that major crops that are cultivated in the study area were still in the field.

Table 6: Characteristics of satellite imageries used

Year	path168/row066	path169/row065	path169/row066
2000	2000-05-11	2000-07-21	2000-07-21
2006	2006-06-05	2006-05-27	2006-05-27
2013	2013-06-08	2013-05-14	2013-05-14

3.2.3 Landsat imagery processing and land use/cover classification

Satellite images were pre-processed before classification was performed. Layer stacking was performed to combine bands and then image edges were trimmed out in ArcMap using the Landsat WRS II path and row shapefiles. Images of the same year but from different path and rows were radiometrically corrected and then mosaicked in ERDAS Imagine 2011 software (Geosystems, 2011). Supervised classification was performed in ArcMap 10.1 (ESRI, 2011) whereby the training sites were selected based on the ground-truth GNSS(Global Satellite Navigation System) coordinates which were collected during field reconnaissance. Other ancillary data like shapefiles of roads, irrigation project maps, rivers and settlements facilitated the selection of classification training samples. Each imagery was classified into 9 land use/cover classes as modified from Anderson scheme of land use/cover classification (Anderson *et al.*, 1976). Land use/cover classes for this study and their details are shown in Table 7.

Table 7: Land use/cover classes and their descriptions

Class	Details
Grassland (GRA)	Tall to short grasses, sometimes bare soils in dry season.
Wetland (WET)	Areas with lands partially covered with water and grasses
Woodland (WOD)	Areas with wood trees but less closed canopy
Forest (FOR)	Areas with closed trees, thick canopy, both natural and planted forests.
Shrubs (SHR)	Short and scatted trees, mainly thorn buses and <i>acacia</i> trees
Agricultural land (AGR)	All land with crops
Bare land (Rock&Soils) (BAR)	Bare soils, rock out crops, quarry areas, sands, eroded soils
Water (WAT)	Rivers, water in wetlands, fish ponds and water in agricultural areas
Urban (URB)	Tarmac and gravel roads, concrete areas, urban and rural settlements

3.2.4 Land Use/Cover Classification Accuracy Assessment

The accuracy of image classification was checked using the ground truthing GNSS points data as well as other reference points which were randomly selected from the features of the satellite images. A maximum of 60 points was selected for each LULC class. As shown in Table 8, the individual accuracy of the LULC types were estimated using the producer's accuracy (omission error) and user's accuracy (commission error). The overall classification accuracy (%) are 87.3, 85.4 and 85.7 for 2000, 2006 and 2013, respectively while the overall kappa statistics for the same years are 0.86, 0.84 and 0.86, respectively.

Table 8: Classification accuracy (%) for LULC maps for the year 2000, 2006 and 2013

Class name	2000		2006		2013	
	Producer Accuracy	Users Accuracy	Producer Accuracy	Users Accuracy	Producer Accuracy	Users Accuracy
Grassland	95.0	79.2	86.7	71.2	91.7	64.0
Wetland	83.6	85.0	85.0	85.0	86.7	85.2
Woodland	85.2	86.7	75.4	86.8	90.0	91.5
Forest	91.7	98.2	93.3	100.0	90.0	96.4
Shrubs	86.7	80.0	93.3	78.9	93.3	94.9
Agric	90.0	81.8	86.7	83.9	90.0	76.1
Bare land (Rock&Soils)	97.5	92.9	75.0	81.1	66.7	100.0
Water	81.0	95.9	86.7	98.1	75.0	100.0
Urban	78.3	94.0	83.3	89.3	81.7	87.5

The producer's accuracy was computed by dividing the number of samples in an individual class identified correctly by the respective reference totals while the user's accuracy was computed by dividing the number of samples in an individual class identified correctly with the classified totals (Lillesand and Kiefer, 1994; Kiptala *et al.*, 2013). The overall classification accuracy was derived by dividing the total number of correctly classified land use classes by the total number of reference data (Kiptala *et al.*, 2013). Kappa statistics, also known as K_{hat} - Coefficient of agreement (Jensen, 2007) was calculated using the following formula;

$$\hat{K} = \frac{N \sum_{i=1}^k x_{ii} - \sum_{i=1}^k (x_{i+} \times x_{+i})}{N^2 - \sum_{i=1}^k (x_{i+} \times x_{+i})} \quad (10)$$

Where k is the number of rows, x_{ii} is the number of observations correctly classified for a particular category (summarized in the diagonal of the matrix), x_{i+} and x_{+i} are marginal totals for row and column i associated with the category, and N is the total number of observations in the entire error matrix. Kappa statistics is a measure of agreement or accuracy between remote sensing-derived classification map and the reference data. Looking at the 2013 users' accuracy on bare land and water, the scores highlight that having local knowledge of the study area has a bearing on the accuracy of the classification. Other studies have found the same pattern (Naidoo and Hill, 2006; Molnár *et al.*, 2008).

3.2.5 Prediction of future land use/cover dynamics

The CA-Markov model was used to predict and model future land use/cover dynamics in Usangu catchment. The CA-Markov is a Change/Time series or Environmental/Simulation model found in IDRISI Selva software. The land use and cover change predication using CA-Markov basically requires three types of data inputs, namely, the basis land cover image, Markov transition areas file and transition suitability images collection. Land cover images are normally prepared through satellite images classification. The land use and cover transition suitability maps are prepared by aggregating a collection of maps (factors and constraints) using the Multi-Criteria evaluation (MCE) method, while the Markov transition areas files are generated by running a Markov module prior to executing a CA-Markov module during the implementation of the Markovian land use and cover change modelling. The land use/cover of Usangu catchment for the year 2020 has been generated using a

Stochastic Markov Model and Cellular Automata in a GIS and Remote Sensing environment to generate data for understanding future water balance in the catchment. Several steps were taken in assessing land use and cover change including:

i) *Preparation Land use and cover suitability maps*: In order to use Cellular Automata, a suitability map for each class is considered as a pre-requirement. Suitability maps are prepared using MCE by combining the information from several criteria to form a single index of evaluation (Eastman, 2012; Baysal, 2013; El-Hallaq and Habboub, 2014). The MCE is a common method for assessing and aggregating weighted maps (criterion) based on experts understanding of the interactions and influence of the factors with land use and cover (Behera *et al.*, 2012; Eastman, 2012). The Usangu catchment's future land use and cover suitability maps were prepared taking into account the factors responsible for land use and cover change and distribution (Canute *et al.*, 2015). These factors are shown in Table 9.

Table 9: Criterion development data sources

Criteria	Criteria source data	Data source	Date
Road distance	GIS database	TANROADS website	-
River distance	GIS database	Rufiji Basin Water Board (RBWB)	-
Settlement distance	Land use map	Classified satellite image	2000, 2006, 2013
Elevation	DEM	Downloaded	-
Slope	DEM	Downloaded	-
Annual precipitation	Met station rain records	Rufiji Basin Water Board (RBWB)	2000, 2006, 2013
Population density	Tanzania census data	National Bureau of Statistics (NBS)	2002, 2012
Soil types	RBWB GIS database	Rufiji Basin Water Board (RBWB)	2014

The factors in Table 9 were aggregated using MCE method and the steps are detailed in Fig. 23. Finding the suitable areas for any land use and cover class requires consideration of different drivers; therefore using a system that evaluates multiple criteria is required. This process combines various criterion (factors and constraints) with different methodologies and then transforms it into a suitability map output (Drobne and Lisec, 2009).

In order to determine a specific class land use suitability in this research under MCE, several steps were involved. These are 1) Identification and development of the criteria, 2)

Standardization of the criteria and 3) Aggregate/combine the criteria to arrive at a suitability map of each land use class.

ii) *Development of Criterion*: The development of criterion for decision making to generate the specific land use and cover suitability map images was possible through the knowledge gained from field survey and insight from literature (López *et al.*, 2001; Weng, 2002; Bürgi *et al.*, 2004; Behera *et al.*, 2012; Eastman, 2012). From the two knowledge sources, different factors and constraints which limit or suit the changing of one land use/cover class to another over time were identified (Table 9), standardized and finally produced suitability maps for each land use and cover class using MCE (Fig. 23).

Factor and constrain images were prepared using ArcGIS Desktop v.10.1 software. Then the images were input in IDRISI Selva v.11 software for further processing. Harnessing the power of Decision Support Wizard in IDRISI Selva, the process of factors and constraints standardization using Fuzzy function up to the Weighted Linear Combination (WLC) aggression step was possible (Fig. 23).

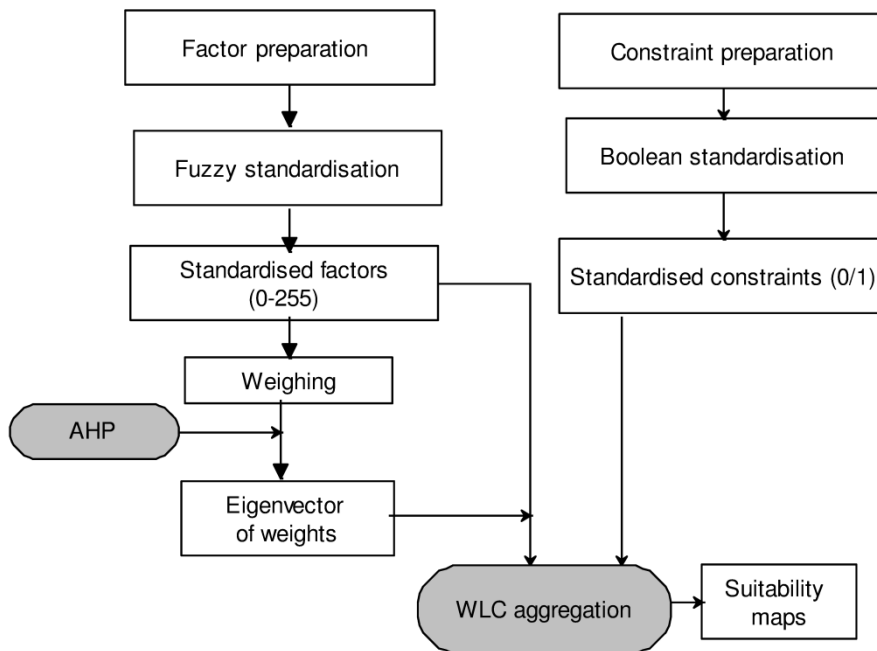


Figure 23: Steps used to prepare land use/cover suitability maps under MCE

During the standardization stage, the factors were stretched from 0-255 using different fuzzy functions and control points (Table 10). The constraint images were standardized as Boolean

images (0/1). The value of “0” represented areas restricted for suitability analysis while “1” represented areas suitable for suitability analysis. Some of the fuzzy membership function types were Sigmoidal, J-shaped and Linear (Eastman, 2009). For each fuzzy membership function (J-shaped, Sigmoid and Linear), the suitability of a given landscape for a particular land use and cover varied different shapes as the value of a factor was increased. These suitability trends could be:

- i. Monotonically increasing: As the value of the factor increases, the suitability of a land surface for a given land use and cover class increases
- ii. Monotonically decreasing: As the value of the factor increases, the suitability of a land surface for a given land use and cover class decreases
- iii. Symmetric: As the value of the factor increased, the suitability of a land surface for a given land use and cover class increased from a certain control point, reached a maximum suitability at a certain point and then started to decrease.

Table 10: Factors, constraints, membership functions and control points used for preparation of suitability maps

Land use suitability class	Factors	Membership function shape	Membership function	Control points	Constraints
Grassland	Distance from railway–road	MI	J-Shaped	$a = 30, b = \text{maximum}$	Existing urban land River course
	Slope	MD	Linear	$c = 0, d = 75$	
	Elevation	MD	J-Shaped	$c = 1020, d = 1100$	
Wetland	Slope	MD	Linear	$c = 0, d = 2$	Existing agricultural land River course Existing urban land Railway–road network
	Distance from urban land	Symmetric	Sigmoid	$a = 4000, b = 7000, c = 7800, d = \text{maximum}$	
	Population density	MD	Linear	$c = 66, d = 1847$	
	Elevation	MD	J-Shaped	$d = 1100, c = 1020$	
Woodland	Distance from railway–road network	MI	Linear	$a = 1000, b = \text{maximum}$	Existing agricultural land River course Railway–road network Existing urban
	Slope	Symmetric	Linear	$a = 2, b = 64, c = 64, d = 65$	
	Distance from urban land	MI	Linear	$a = 4000, b = \text{maximum}$	
	Population density	MD	J-shaped	$c = 1, d = 41$	
	Elevation	MI	Linear	$a = 1100, b = 2000$	
	Annual Rain	MI	Linear	$c = 700, b = 1100$	
Forestland	Distance from railway–road network	MI	Linear	$a = 1000, b = \text{maximum}$	Existing agricultural land River course Railway–road network Existing urban
	Slope	Symmetric	Linear	$a = 2, b = 25, c = 50, d = 65$	
	Distance from urban land	MI	Linear	$a = 2000, b = \text{maximum}$	
	Population density	MD	Linear	$c = 1, d = 40$	
	Elevation	MI	J-shaped	$a = 2000, b = \text{maximum}$	
	Annual rain	MI	Linear	$a = 901, b = \text{maximum}$	
Shrub land	Distance from railway–road network	MI	Linear	$a = 50, b = \text{maximum}$	River course Railway–road network Existing urban land
	Distance from urban land	MI	Linear	$a = 100, b = \text{maximum}$	
	Elevation	Symmetric	Linear	$a = 1100, b = 2000, c = 2000, d = 2962$	

Land use suitability class	Factors	Membership function shape	Membership function	Control points	Constraints
Agric land	Slope	MD	Linear	$d = 15, c = 1$	River course Railway–road network Protected areas Wetlands
	Distance from urban land	Symmetric	Linear	$a = 100, b = 500, c = 4000, d = \text{maximum}$	
	Population density	MD	Linear	$c = 100, d = 170$	
	Elevation	MD	Sigmoid	$c = 1000, d = 2000$	
Bare land	Slope	MD	J-shaped	$c = 0, d = 9.9$	River course network Railway–road network Existing urban
	Distance from urban land	Symmetric	Symmetric	$a = 10, b = 30, c = 30, d = 500$	
	Elevation	MI	J-shaped	$a = 1020, b = 2000$	
	Soil types	Do not fuzzy	-	-	
	Annual rain	MD	Linear	$a = 500, b = 700$	
Water	Existing water network (Boolean)	No fuzzy	-	-	-
Urban land	Distance from urban land	MD	J-shaped	$a = 400, b = \text{maximum}$	Existing water surfaces River course (60m buffer) Protected areas Wetlands
	Distance from railway–road network	Symmetric	Linear	$a = 1, b = 2000, c = 2000, d = 4500$	
	Slope	MD	Linear	$c = 7, d = 15.1$	
	Population density	MD	Linear	$a = 171, b = \text{maximum}$	

Note: MD: Monotonically Decreasing, MI: Monotonically Increasing

Since the final determination of suitability of a specific land use class is achieved through aggregation (overlay) of the factors, the overlay requires the standardized factors to be weighted based on their relative importance in influencing the suitability of a certain landscape surface for a given land use and cover class. The weighted overlay of factors can be done using three approaches; using user defined weights, assigning equal weights or using Analytic Hierarchy Process (AHP) (Malczewski, 1999, 2006). In this study, the AHP was adopted. The final AHP Eigenvector of weights facilitated to perform aggregation of the standardized factors and the standardized constraints using a WLC algorithm (Malczewski, 2000). The WLC aggregation under the MCE generated the standardized suitability maps for each land use and cover class (Fig. 24). The standardized suitability maps are among the important data input in CA-Markov model.

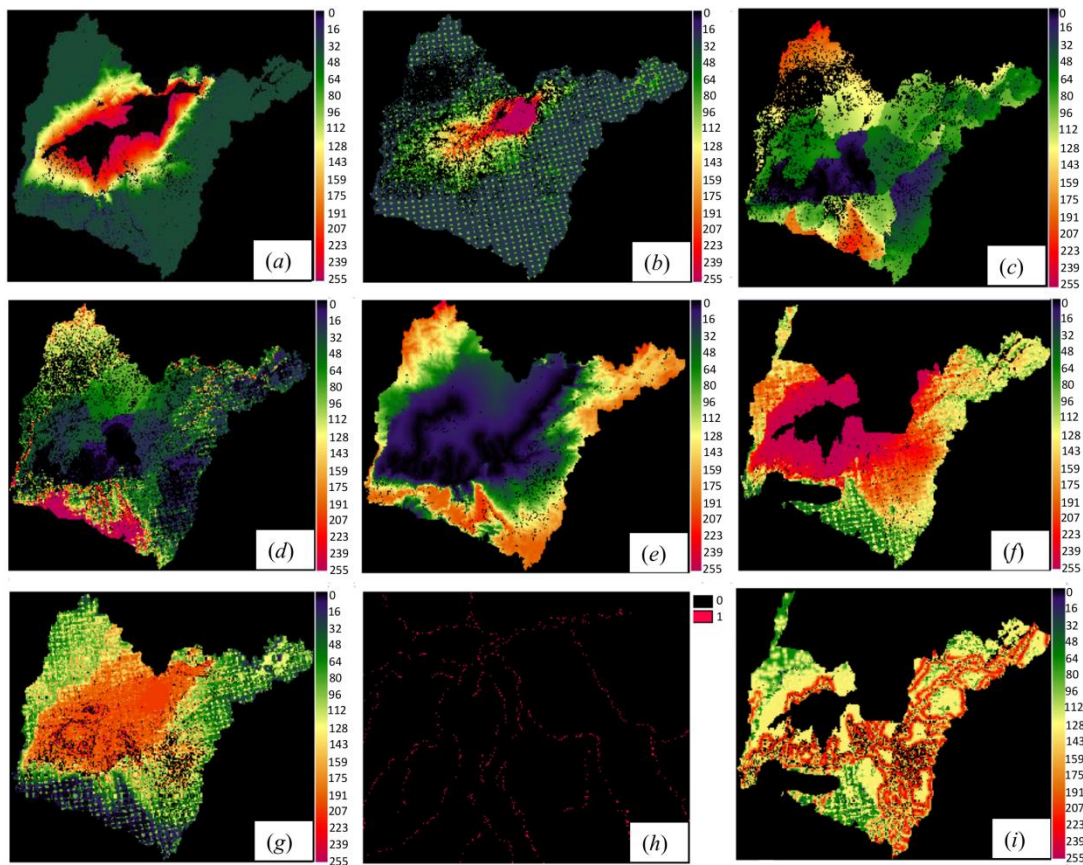


Figure 24: Land use and cover classes suitability maps for grassland (a), wetlands (b), woodland (c), forestland (d), Shrubs (e), agricultural land (f), barren land (g), water (h), and urban land (i). The “Quant” Palette file in IDRISI Selva is used to display colour of raster images. The colour is scaled from 0-255, except (h) where “0” denotes a restricted area for suitability analysis and “1” represents areas suitable for suitability analysis

3.2.6 Land use/cover change prediction framework

Land use and cover dynamics of Usangu catchment for the year 2020 was simulated by employing the Stochastic Markovian model using IDRISI software. The procedure to accomplish the task is presented in Fig. 25. The procedure shown in Fig. 25 starts with running Markov module using the land use and cover of two time scale, land use and cover of 2000 as the earlier land cover image ($t-1$) and land use and cover of 2006 as the later land cover image ($t=1$). The Markov module generated two text files namely Transition probabilities file (Table 11) and Transition areas file. Transition probabilities file express the likelihood that a pixel of a given class will change to any other class (or stay the same) in the next time period (Eastman, 2012); while a transition areas matrix expresses the total area (in cells) expected to change in the future time period.

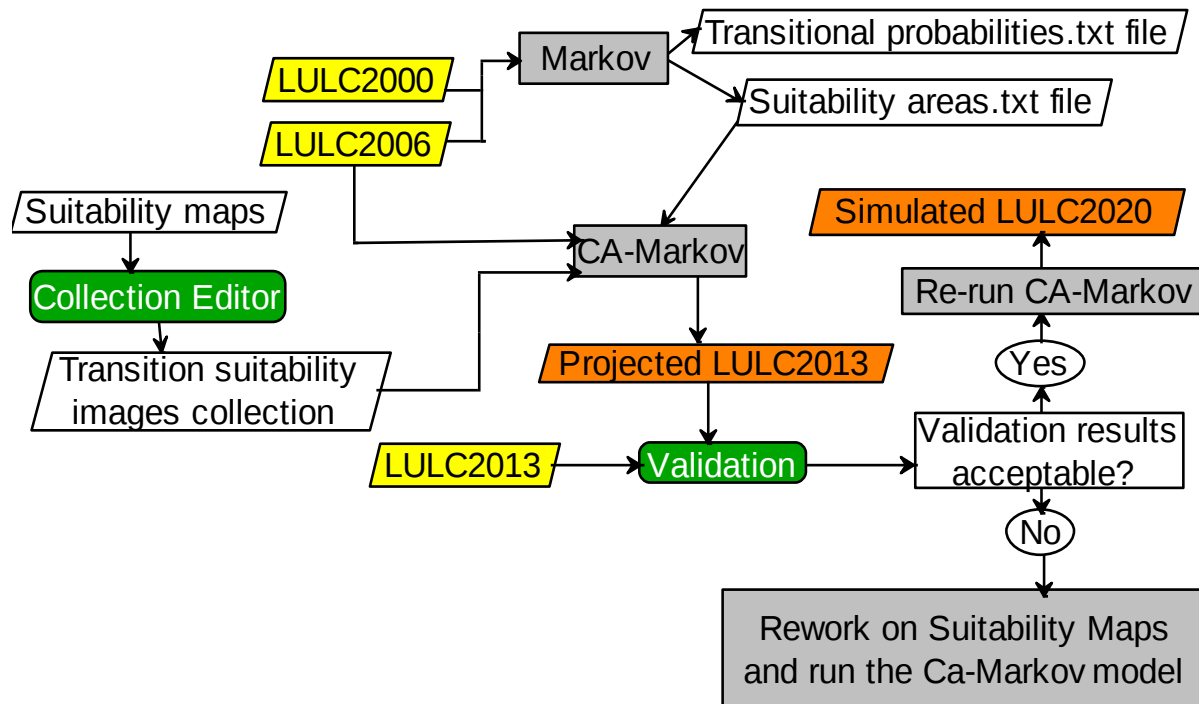


Figure 25: CA-MARKOV modelling steps to achieve simulated land use and cover of 2020

The Markov module outputs were combined with the suitability maps using CA-Markov module to predict land use and cover of 2013 using 5×5 contingency filters. The observed and simulated land use and cover maps of 2013 (Fig. 26a&b) are for model validation. The importance of model validation as an important stage in the development of any predictive change model has been stressed by previous researchers (Ewen and Parkin, 1996; Pontius *et al.*, 2001; Pontius and Schneider, 2001; Eastman, 2012).

Several methods for validation of future land use and cover change prediction models are available. Such methods include, i) Chi-Square-F-test of two images for variance (Muller and Zeller, 2002; Weng, 2002; Katana *et al.*, 2013), ii) kappa coefficient (κ) and Cramer's V (Pontius and Millones, 2011; Baysal, 2013), and iii) quantity disagreement and allocation disagreement approach (Pontius and Millones, 2011; Baysal, 2013; Brown *et al.*, 2013).

In this study, the model was validated using the approach proposed by Pontius and Millones (2011). This approach proposes to use some simple but meaningfully measures: quantity disagreement and allocation disagreement approach (12). Validation results consists of statistical analysis that shows the level of agreements of the simulated and observed land use/cover maps in terms of the quantity of cells in each category and also the level of agreement of pair of maps in terms of the location of cells in each category (Eastman, 2012). The κ indices were also used to assess the accuracy of the simulation model. In this study, the acceptable level of agreement between observed and simulated maps were set to a minimum kappa values of 0.61 ("substantial agreement") and above. After obtaining such values, the CA- Markov model was accepted, then employed to simulate the land use and cover of 2020 (Fig. 27).

3.3 Results

3.3.1 Land use/Cover Classification Accuracy

The overall classification accuracy of the classification for 2000, 2006 and 2013 were 87.3, 85.4 and 85.7%, respectively. The overall Kappa Statistics for the 2000 imagery was 0.86 while for 2006 and 2013 was 0.84. The USGS satellite imagery classification scheme has set the minimum standard for accuracy assessment to be 85% (Anderson *et al.*, 1976; Weng, 2002). Generally, the results of classification accuracy assessment in this study are acceptable. Kappa values greater than 0.80 (i.e. >80%) represent strong agreement or accuracy between the classification made and the ground reference information (Jensen, 2007).

3.3.2 The probabilities of land use and cover change

The probability transition matrix for simulation of land use and cover of the year 2013 by using land use and cover images of 2000 and 2006 is shown in Table 11. The categories of earlier date, $t-1$ (2000) are shown in rows while the columns show the same categories of

later date, $t=1$ (2006). The bolded values in the diagonal show the probability of a given land use and cover category to remain stable after a given time lapse from earlier to later time. The land use and cover category with high probability to remain unchanged is grassland (0.4328) and woodland (0.4091). Generally, values in the diagonal (Table 11) showed that the probability of most of land use and cover categories (except Grassland and woodland) to remain stable in the future is low.

If the wetland could change its state to other land use and cover classes, there is a probability of 0.4230 and 0.1685 that it will change to grassland and agricultural land, respectively. The probability transition values showed that there is no possibility of other lands that can change to water except the small probabilities for natural neighbours of water, namely wetlands (0.0003), agriculture (0.0002) and bare lands (0.0001).

Table 11: Probability transition matrix for simulation of land use and cover in year 2013 by using land use and cover images of 2000 and 2006

Given:	Probability to change to:								
	GRA	WET	WOD	FOR	SHR	AGR	BAR	WAT	URB
GRA	0.4328	0.0708	0.1121	0.0081	0.1669	0.1348	0.0551	0.0000	0.0194
WET	0.4230	0.2080	0.0015	0.0004	0.1410	0.1685	0.0340	0.0003	0.0232
WOD	0.1387	0.0212	0.4091	0.0399	0.2412	0.1464	0.0000	0.0000	0.0035
FOR	0.0766	0.0000	0.4698	0.2231	0.1715	0.0530	0.0037	0.0000	0.0024
SHR	0.1971	0.0359	0.2972	0.0312	0.2696	0.1459	0.0143	0.0000	0.0088
AGR	0.3415	0.1386	0.1635	0.0107	0.1476	0.1625	0.0181	0.0002	0.0173
BAR	0.5144	0.1163	0.0000	0.0000	0.1346	0.1242	0.0859	0.0001	0.0245
WAT	0.4030	0.0973	0.0315	0.0032	0.2055	0.1525	0.0606	0.0002	0.0461
URB	0.3555	0.1151	0.0227	0.0039	0.1139	0.1680	0.0945	0.0000	0.1263

Note: GRA: Grassland, WET: Wetlands, WOD: Woodlands, FOR: Forestland, SHR: Shrubland, AGR: Agricultural land, BAR: Bare land, WAT: Water and URB: Urban land

3.3.3 Model validation results

The land use and cover 2013 that was used for validation of the future land use and cover prediction model is presented together with the actual land use and cover 2013 in Fig. 26a&b. They showed high degree of similarities in terms of spatial distribution of all land use and cover classes. On both Fig. 26a&b, the land use and cover classes such as the wetlands

appeared to be distributed in the central parts of the images, surrounded by grasslands and patches of agricultural lands. The woodlands and forests were distributed in the Southern and the North-west parts. The urban lands were found on the areas along the roads such as Makambako, Uyole and Mafinga.

The values of quantity disagreement and allocation disagreement between the simulated and observed land use and cover 2013 maps are presented in Table 11. The values showed that the overall agreement between reality and simulation maps of 2013 was 0.9125 while the overall simulation error was 0.0876 which can be partitioned into 0.0243 (error due to quantity/ DisagreeQuantity) and 0.0633 (error due to allocation/ DisagreeGridcell). In addition the agreement and disagreement measures in 12, the VALIDATE module generated kappa coefficient (κ) values: 0.6776, 0.9028 and 0.7441 for κ -standard, κ -no (κ for no information) and κ -location (κ for location), respectively.

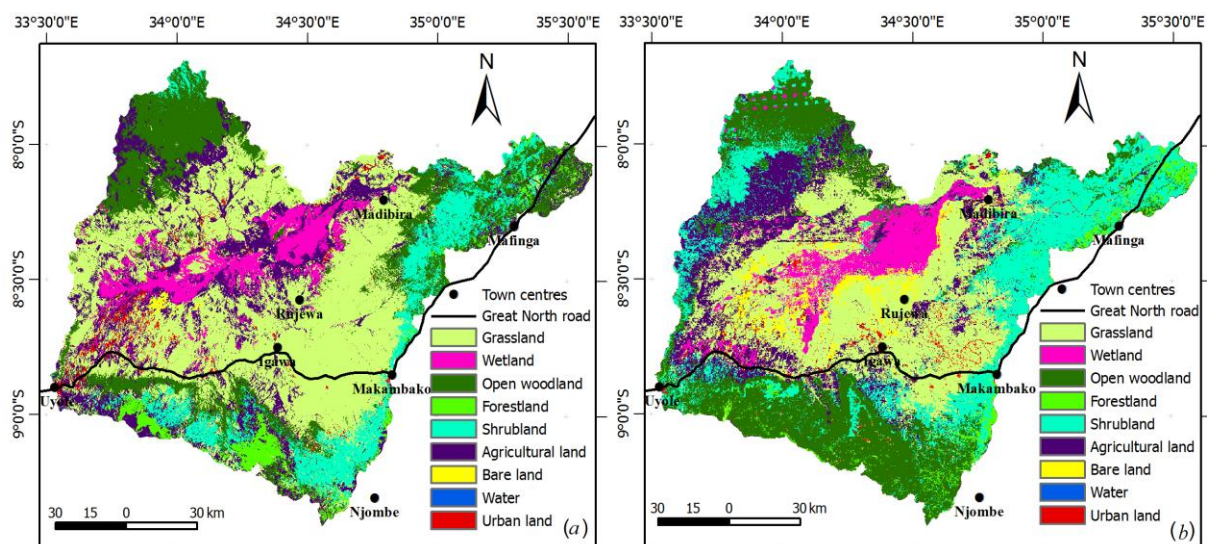


Figure 26: Observed land use and cover of 2013(a) and Simulated land use and cover 2013 (b) (Sources: Fig. 25 (a) adopted from Canute et al., 2015)

Table 12: Results of validation analysis-Agreement/disagreement components

Agreement/Disagreement	Value
Allocation disagreement	0.0633
Quantity disagreement	0.0243
Overall simulation error	0.0876
Allocation agreement	0.1840
Quantity agreement	0.6285
Chance agreement	0.1000
Overall agreement	0.9125

3.3.4 Simulated land use and cover of 2020 and dynamics

Visual interpretation of land use and cover of 2020 (Fig. 28) showed that the land use and cover change prediction model used in this study to predict the land use and cover 2020 had great efficiency in terms of spatial location and distribution of most of land use and cover categories relative to their original locations in the parent image (Fig. 26b). Worthy mentioning, natural neighbour land use and cover classes such as the woodlands and forests, wetlands and agriculture, agriculture and grasses showed a good neighbourhood spatial association.

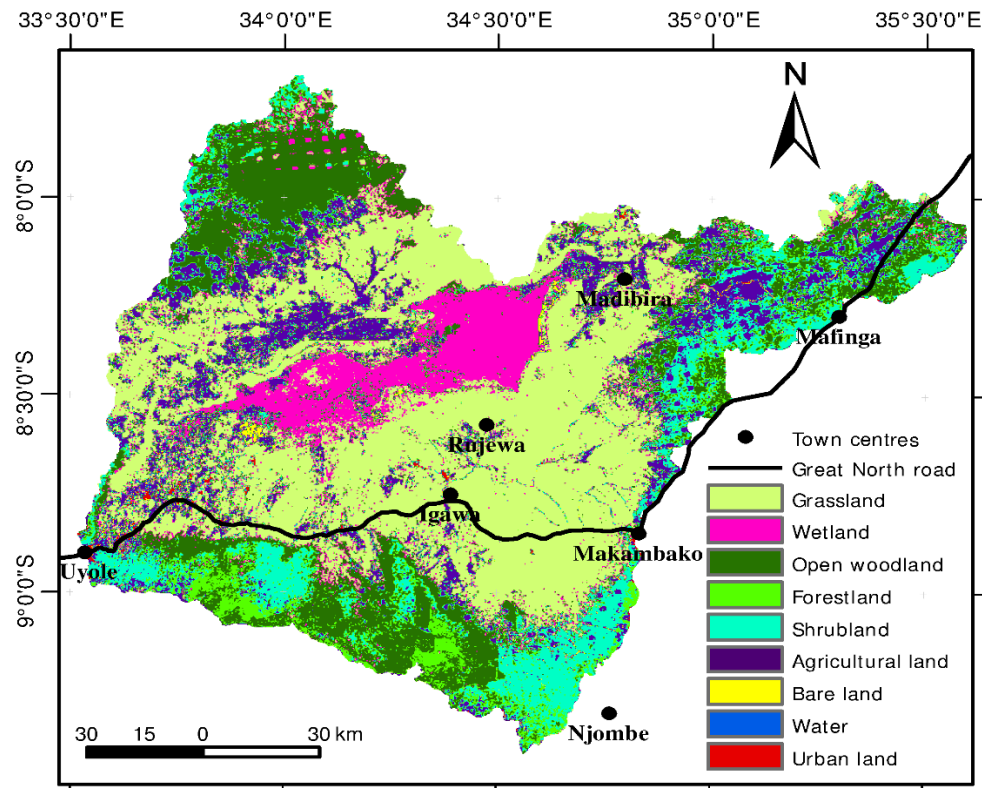


Figure 27: Simulated land use and cover of 2020 of Usangu Catchment

The dynamics of land use and cover from the year 2013 to 2020 (Table 13) showed that for the period 2013-2020 the urban land will increase by 8.2%, while a major decrease will be observed in forestland (20.6%) and shrubs (6.9%). Of all urban land in 2020, about 59.3km² (19.6%) will have been converted from grassland while 25.8 km² (8.5%) will be from agricultural land. The model results (Table 13) predicts a little expansion of agriculture from 2013 to 2020 (1%). Major land use/cover classes that might be transformed into agricultural land are grasslands (375.7 km²/10.5%), wetlands (372.0 km²/10.4%) and woodlands (368.2 km²/10.3%).

Table 13: Land use and cover change matrix for 2013-2020 (km²)

		2013										
Land use/cover Class		GRA	WET	WOD	FOR	SHR	AGR	BAR	WAT	URB	Total 2020	
2020	GRA	7767.6	308.4	138.4	20.8	81.9	375.7	5.8	0.1	59.3	8758.1	
	WET	186.5	925.1	34.0	0.3	9.4	372.0	9.8	0.0	6.9	1543.9	
	WOD	119.8	3.3	2852.5	163.2	371.5	368.2	0.1	0.0	4.8	3883.4	
	FOR	46.4	0.1	28.4	386.7	36.2	53.9	0.0	0.0	0.8	552.5	
	SHR	262.2	8.5	237.7	54.5	1138.1	296.8	6.1	0.1	11.0	2014.9	
	AGR	290.8	115.0	585.5	39.0	491.6	2067.9	8.5	0.0	25.8	3624.1	
	BAR	22.3	15.5	0.4	0.0	0.0	27.7	27.9	0.0	5.6	99.4	
	WAT	0.0	0.4	0.0	0.0	0.0	0.3	0.0	0.4	0.0	1.1	
	URB	71.3	4.7	11.8	2.0	25.9	25.1	0.6	0.0	188.7	330.0	
Total 2013		8766.9	1381.0	3888.5	666.6	2154.6	3587.5	58.8	0.6	303.0	2 0807.4	
%Change		-0.1	10.6	-0.1	-20.6	-6.9	1.0	40.9	46.7	8.2		

Note: The negative (-) sign in the last row indicates the decrease in area. GRA: Grassland, WET: Wetlands, WOD: Woodlands, FOR: Forestland, SHR: Shrub land, AGR: Agricultural land, BAR: Bare land, WAT: Water and URB: Urban land

3.4 Discussions

3.4.1 Probabilities of land use and cover change

The probabilities of one land use and cover class to change into another class as observed for wetland changing to grassland and agricultural land (0.4230 and 0.1685, Table 11) as well as other lands classes changing to water such as wetlands (0.0003), agriculture (0.0002) and

bare lands (0.0001) could be owed to their proximity. It is contended by Eastman (2012) that one of the basic spatial elements that underlies the dynamics of many change events is proximity. Other researchers (Sun *et al.*, 2007; Memarian *et al.*, 2012) demonstrated that areas will have a higher tendency to change to a class when they are near existing areas of the same class. A cellular entity will independently vary its state based on its previous state and that of its immediate local neighbours (Eastman, 2012). In this study, the land use and cover change probabilities based on neighbourhood relationship is also observed between forest and woodlands (Table 11). If forestlands are to change to other land use and cover types, there is a great probability (0.4091) that it will change to woodlands than other classes. The observation in the field found out that agricultural cultivation is also carried out in seasonal wetlands and this could also justify the high probability (0.4230) of wetlands changing to agricultural lands in the future.

The low probability values in the diagonal in Table 11 which indicate low possibilities for most of land use and cover classes to remain stable in the future would imply that the Land use and cover categories are very dynamic in the catchment. Some of the factors which may be contributing to this include agricultural fallow practices (Canute *et al.*, 2015) and the year to year fluctuations in rainfall amounts as reported by Kashaigili *et al.* (2005). The low probability (0.2231) of areas under forestlands to remain stable in the future could also be associated with the commercial forests (Makambako and Mafinga) which involves planting and harvesting of trees for timber and paper industry. The land under irrigated rice farms in different locations of the catchment are also very dynamic and unpredictable temporally due to its dynamic response to the amount of available water (Lankford and Franks, 2000). This nature of agricultural practices, together with the recent relocation of settlements from the areas close to Ihefu wetland (Ngailo, 2013) may also be linked with the low probability values for urban and agriculture in the diagonal (Table 11), otherwise they would have shown high probability of permanence as it was observed in Upper Athi River Catchment, Kenya, by Katana *et al.* (2013).

3.4.2 Evaluation of model validation results

The good match between the actual land use and cover from image classification (observed) and the simulated results from CA-Markov of the year 2013 in Fig. 26a&b could mostly be

attributed to the good quality and realistic suitability maps shown in Fig. 24 that were used as input data for simulating land use and cover 2013. According to Sun *et al.* (2007) the suitability maps have a great influence on the land use predictions because they act as the rules for the Cellular automata model. Different suitability maps lead to different rules that in turn may produce very different results. The good quality of suitability maps used in the CA-Markov prediction in this study could also be associated to the overall agreement index of 0.91 between the CA-Markov simulated and actual land use and cover 2013 (Table 12).

Looking at the agreement components values in Table 12, they show that the proportion of quantity agreement (0.6285) is larger compared to allocation agreement (0.1840). This implies that the calibration process resulted into a simulation model that generated a comparison map (simulated) with more capability of specifying the correct quantity of each category to the reference map than it does for the allocations. Similar results for high values of quantity and allocation disagreements were found in Langat Basin, Malaysia (Memarian *et al.*, 2012). The CA-Markov model did not accurately simulate land use change dynamics in this area.

The allocation agreement can be improved by changing cell resolutions of the land use image map from fine to coarse resolution (Pontius, 2002). It is common that many cells disagree on a cell-by-cell basis, especially if the georeferencing and geometric correction of the comparison map was not done well (Eastman, 2012). If the analysis is performed at a slightly coarser resolution, then the level of cell-by-cell disagreement in this study could convert to high agreement values shown in the graph of MBR versus Allocation disagreement (Fig. 28). The graph showed that the level of allocation disagreement (Allocation error) in this research could be reduced by changing the image resolution by a factor of three (3×3). Beyond this point, there would be very little improvement in reducing the level of allocation disagreement between the simulated and observed land use/cover maps. This indicates that in this study the simulated maps had very near misses of spatial locations of the pixels relative to actual maps (Pontius, 2002). According to this author, if there are many near misses in the comparison at the finest resolution, then the agreement between the maps will rise rapidly in the early stages of aggregation. If there are many far misses, then the agreement will not rise (level of disagreement will not be reduced) until later stages of aggregation (or high level of MBR).

The MBR versus Quantity disagreement line shows that the level of disagreement due to quality error cannot be improved by changing the image cell resolutions. It remained constant at about 0.025 throughout different multiple base resolution levels.

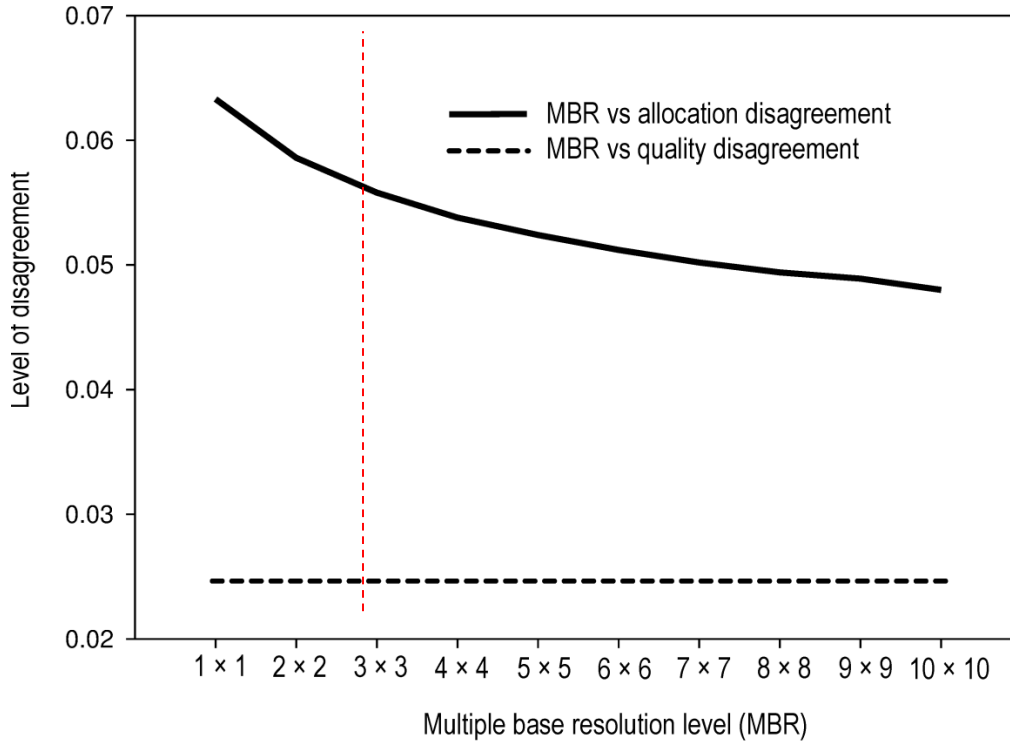


Figure 28: Changing quantity and allocation error by changing images resolutions

The κ -standard value 0.67 from the VALIDATE module is above the acceptable minimum objective that was set for this study (0.61). All kappa coefficient (κ) values ranged from 0.6776 - 0.9028, which can be described as “substantial” agreement to “almost perfect” agreement (Viera and Garrett, 2005).

The value for κ -standard in this study is a slightly lower than those which have been reported in other studies which applied CA-Markov model in land use and cover change predictions, such as, 0.766 (Mitsova *et al.*, 2011), 0.9545 (Habboub, 2013), and 0.85 (Memarian *et al.*, 2012). The slightly lower values in this study could probably be attributed to some errors in images geometric correction and misclassification of some pixels into different classes which could lead to location disagreements between predicted and actual maps (Pontius, 2002) or some quality of suitability maps of some land use and cover classes such as water and bare land. The suitability maps have great influence on the land use predictions (Sun *et al.*, 2007).

Other reasons could be errors in calibrating the suitability maps, generalizations applied for image classification or the shape of the contiguity filter used during the prediction of future land use (Araya and Cabral, 2010).

3.4.3 Future land use/cover and dynamics

Visual interpretation of land use and cover of 2020 (Fig. 27) showed that the model used for change prediction of land use and cover 2020 had great efficiency in terms of spatial location and distribution of most of land use and cover categories relative to their original locations in the parent image (Fig. 26b). Worthy mentioning, natural neighbour land use and cover classes such as the woodlands and forests, wetlands and agriculture, agriculture and grasses showed a good neighbourhood spatial association.

The dynamics of land use and cover from the year 2013 to 2020 (Table 13) showed that for the period 2013-2020 the urban land will increase by 8.2%, while a major decrease will be observed in forestland (20.6%) and shrubs (6.9%). Of all urban land in 2020, about 59.3km² (19.6%) will have been converted from grassland while 25.8 km² (8.5%) will be from agricultural land. Furthermore, the land use and cover change matrix table (Table 13) indicate only 1% expansion of agriculture from 2013 to 2020. Major land use and cover classes that might be transformed into agricultural land are grasslands (375.7 km²/10.5%), wetlands (372.0 km²/10.4%) and woodlands (368.2 km²/10.3%).

A good match between simulated and observed land use and cover 2013 (Fig. 26a&b) and eventually the simulated land use and cover 2020 (Fig. 27) with close to reality spatial location and distribution of most of land use and cover categories is mostly attributed to the ability to prepare realistic suitability maps and transition matrix. According to other researchers (Verburg *et al.*, 2006; Memarian *et al.*, 2012), the realistic suitability maps and transition matrix are the foundations for the good future land use and cover prediction in CA-Markov model. The suitable transition matrix for creating a future model depends also on how well the requirements necessary for creating a suitable transition matrix are addressed (Peña *et al.*, 2007).

The increase of the area under urban land by 8.2% between 2013 and 2020 could be attributed to expected population growth in the catchment in the future. This will result into

increased area under urbanization, especially along road network and in the urban fringes. One of the possible factors that attract the influx of people from other regions into Usangu catchment to harness the existing agriculture potential is the rice and onions which have been catching good prices in recent years (Canute *et al.*, 2015). This, in turn, will also lead into conversion of some portions of other land use and cover types such as wetlands, forests and grasses to meet the new land demands for the urban and agricultural production.

The 2020 land use and cover model predicts a very big increase in the proportion of land under water (46.7%) and bare lands (40.9%) (Table 13). Despite the difficulties encountered in this research to prepare the transition suitability maps for prediction of these two land use and cover categories as previously observed elsewhere (Kamusoko *et al.*, 2009), such high increase may be explained by the anticipated changes in other land use and cover categories. For example, new irrigated agricultural areas and canals will create the possibility of having more areas covered by water (Xiao *et al.*, 2006). This will result to stagnant water surfaces in farms and in drainage channels close to agricultural areas. The projected increase in the bare lands shown in Table 13 is largely a result of transformation of some portions of other land uses to bare lands, mainly grassland (22.3 km²) and agricultural lands (27.7 km²). The expansion of urban lands and agriculture has also a high probability of resulting in expanding the bare lands. the increase in bare land areas on the other hand imply severe land degradation in the future (Kamusoko *et al.*, 2009).

The observed future increase in agricultural land and decrease in forests in this study are most likely to have adverse impacts on water balance of the Usangu catchment such as reduced infiltration and increased surface runoff as observed in other studies in other areas (Mulungu and Kashaigili, 2012; Shawul *et al.*, 2013; Monteiro *et al.*, 2016). The expansion of agriculture and settlements were found to be the main causes of changes in hydrological systems in the Shaya mountainous watershed in Southern Ethiopia (Shawul *et al.*, 2013). The land use and cover changes in the watershed could also result in the changes in the performance characteristics of the watershed (water balance), including water infiltration rate, runoff and base flow (Zhang and Schilling, 2006; Mulungu and Kashaigili, 2012). The increased surface runoff and reduced infiltration resulting from changes such as increased bare lands and reduced forest cover could probably result into reduced dry season base flow

(Kashaigili, 2008) and quick arrival of water in wetlands in the lower altitudes of the study are after rainfall events.

3.5 Conclusion

Land use and covers of Usangu catchment are very dynamic. In the period from 2013-2020, the land area under urban, bare lands and agricultural lands will continue to increase while forest lands will decrease. The predicted changes are a warning signal to environmental management experts in the catchment to prepare good and future based land and water management strategies. Such strategies should ensure the expected urban and agricultural expansion do not cause adverse environmental impacts such as deforestation and loss of water through evapotranspiration.

Land use and cover classes which constitute a small percentage of the total catchment surface area such as water and urban lands presented a serious challenge in the accuracy of future land use and cover simulations. It is proposed that further studies to be carried out to find some new ways to develop the criterion for suitability maps of these land use and cover categories might improve the accuracy in simulating their future dynamics.

The CA-Markov model validation results show that the quantity agreement was greater than the allocation agreements. This suggests that there is a need to improve the geometric corrections of the previous time ($t-1$) and the current time (t) satellite images before modelling is done. The assessment of the accuracy of the simulated 2020 land use and cover ($t+1$) was based on the transition matrix results, the spatial locations of land use and cover classes of previous time (t) image and the spatial association between the natural neighbour land uses. Such approach suggests that attention should be paid during the time of the preparation of suitability maps as well as the transition matrices. Once the suitability maps, as well as the transition matrices are accurately prepared, then, good results of predicted future land use and cover ($t+1$) are guaranteed.

Generally, the CA-Markov land use predictive model of Usangu catchment has generated plausible and satisfactory simulation results for short-term forecasting of land use and cover change. The procedure designed for development of suitability maps and subsequent land use and cover change prediction model in this study is very useful as it provides an insight and

possibility for future based planning and management of the watershed. It can be easily used in later times (after 2020) in the same watershed or borrowed to model land use and cover change in other catchments with minimum modifications of the control points and membership functions which were used to prepare suitability maps in this study.

CHAPTER FOUR

The impact of future climate and land use/cover change on water resources in the Ndembera watershed and their mitigation strategies²

Abstract

The impact of near future (2010-2039) climate and 2020 land use/cover change on water balance and streamflow of Ndembera River watershed in Usangu catchment, Tanzania is assessed using Soil and Water Assessment Tool (SWAT). The same tool was used to evaluate the effectiveness of four land and water management practices as the mitigation strategies in reversing the adverse impacts of climate and land use changes. The 2020 land use/cover was predicted using Markov chain and Cellular Automata models based on 2006 and 2013 land use/covers. The near-future climate scenario was generated from the Coupled Model Intercomparison Project 5 General Circulation Models. Results showed that from 2013-2020 agricultural land and evergreen forests will increase by nearly 10% and 7%, respectively. Mixed forests will decrease by 12%. Such land use/cover changes will decrease the total water yield by nearly 13% while increasing evapotranspiration and surface runoff by approximately 8% and 18%, respectively. Warmer near-future mean annual temperatures (1.1°C) and wetter conditions (3.4 mm/year) than in the baseline period (1980-2009) will aggravate this moisture balance changes. The warmer future climate will increase evapotranspiration and decrease water yield by approximately 35% and 8%, respectively. The management practices such as filter strips can reduce the annual evapotranspiration by 6%, and increase stream-flow by 38% in February. The study demonstrates that land and water management practices have great potential to mitigate the impacts of future climate and land use/cover changes on water resource, thus increasing its availability.

Keywords: Water balance, Soil and Water Assessment Tool, climate change, land and water management practices, Usangu catchment, Tanzania

² Environmental Systems Research Journal, <https://doi.org/10.1186/s40068-018-0110-4>

4.1 Introduction

Land use/cover and climate changes have a great influence on the hydrological response of a watershed (Kashaigili and Majaliwa, 2013; Kirby *et al.*, 2016). The hydrological processes which are affected by such changes include evapotranspiration, infiltration, surface runoff, groundwater flow and stream discharge regime (Natkhin *et al.*, 2015). The effects of the land use/cover and climate change on hydrological processes are set to increase in the future due to the increased clearance of virgin forest lands for agriculture and the rise of global warming (Fischer, 2013). Thus, the way in which the future climate will interact with the land use changes and affect the water balance in the watersheds requires more attention.

There is evidence to suggest that Tanzania is among the countries in Africa which is most at risk of being impacted by climate change (Hatibu *et al.*, 1999). Further, it is anticipated that the farming sector will experience more impacts resulting in decreased production of different crops due to decreased water availability and the shift of growing seasons (Laderach and Eitzinger, 2012; Kangalawe and Lyimo, 2013). Although the climate change is predicted to cause adverse impacts on freshwater resources, especially in the dry sub-tropical regions (Pervez and Henebry, 2015; Serdeczny *et al.*, 2016), there is a little consideration given to the impacts in the process of planning of future water resource use and management (McCartney *et al.*, 2012). Studies of the impacts of climate change on water resource are, therefore, encouraged to ensure its sustainability.

Usangu Catchment, a part of the Rufiji Drainage Basin, is important for rice production in Tanzania. It produces more than 30% of the country's rice and supports over 30,000 rice-producing households on approximately 115,000 ha of irrigated land (WB,2017). Rice and onions have captured good market price in the recent years, which in turn has brought a huge influx of Tanzanians into the catchment area to grow these crops. As a result, forest and wetlands along the rivers including the Ndembera River are converted into small-irrigated farms. Kashaigili (2008) showed that there is a clear linkage between land use/cover changes and the changes in hydrological regime for the Usangu wetlands and the Great Ruaha River in the Usangu catchment. It is therefore important to assess the changes in water balance and river discharge resulting from the land use/cover changes taking place in the Ndembera River watershed.

The historical land use/cover changes and their impacts on water resources in Usangu Catchment have been widely studied (Kikula, 1996; Kashaigili *et al.* 2006a; Kashaigili, 2008). For example, Kashaigili *et al.* (2006a) observed a decline in water inflow into the Usangu Wetland due to the expansion of agricultural activities through forests clearing in the upstream. Indeed, some few land and water management practices have been applied in Usangu Catchment to improve the moisture holding capacity of soils. These included afforestation programs (Kashaigili *et al.*, 2009), growing trees and shrubs (Malley *et al.*, 2009a) and contour bunds and terraces (Mwanukuzi, 2011). There are other practices such as filter trips, contour and terracing and grassed waterways which could also be used (Arnold *et al.*, 2013). However, there is limited information about how effective these management practices have been in slowing the impact of climate and land use/cover change on water resources in Usangu Catchment.

This study was, therefore, carried out to assess the impact of the future (2020) land use/cover change and the near future (2010-2039) climate change effects on water balance and streamflow of the Ndembera River watershed in Usangu catchment. Further, the effectiveness of land and water management practices in mitigating the impacts of future climate and land use changes on water balance and streamflow was evaluated.

4.2. Material and methods

4.2.1 Study area

The Ndembera River watershed is located in Usangu Catchment, in the southern highlands of Tanzania (Fig. 29). It covers an area of about 1705 km². Ndembera is one of the five perennial rivers in the Usangu Catchment, in the Rufiji Basin (SMUWC, 2001b). The river originates from the springs of Udumka Village (Fig. 29), at an elevation of about 2060 metres above sea level (m.a.s.l). This river accounts for about 15% of the total flow of the Great Ruaha River (Elzein, 2010). The section of the watershed which is considered in this study drains from Udumka Village to a river gauging station (1ka33). Water from Ndembera River supports about 16 large scale farms and irrigation schemes located at Udumka, Ihemi, Ifunda, Muwimbi, Igomaa, Mkunywa and Mahango villages as well as the Madibira irrigation scheme located near Madibira town (Fig. 29).

The rainfall of the watershed is unimodal, with one wet period (Early November to the end of April) and one dry period (Early May to the end of October). The precipitation is uni-modal, and its spatial distribution is strongly influenced by topography. The highlands receive precipitation of about 1600 mm/year, while the plains receive around 500-700 mm/year (Shu and Villholth, 2012).

The Ndembera river watershed was chosen for SWAT simulation among other watersheds due to a number of reasons. First, Ndembera River contributes about 15% of the total flow of the Great Ruaha River. Second, there a good number (16) of irrigated farms in the watershed (Fig. 29). Lastly, there are two river flow gauging stations with the data that were enough to realise long time simulation of the river flow (1ka15 and 1ka33).

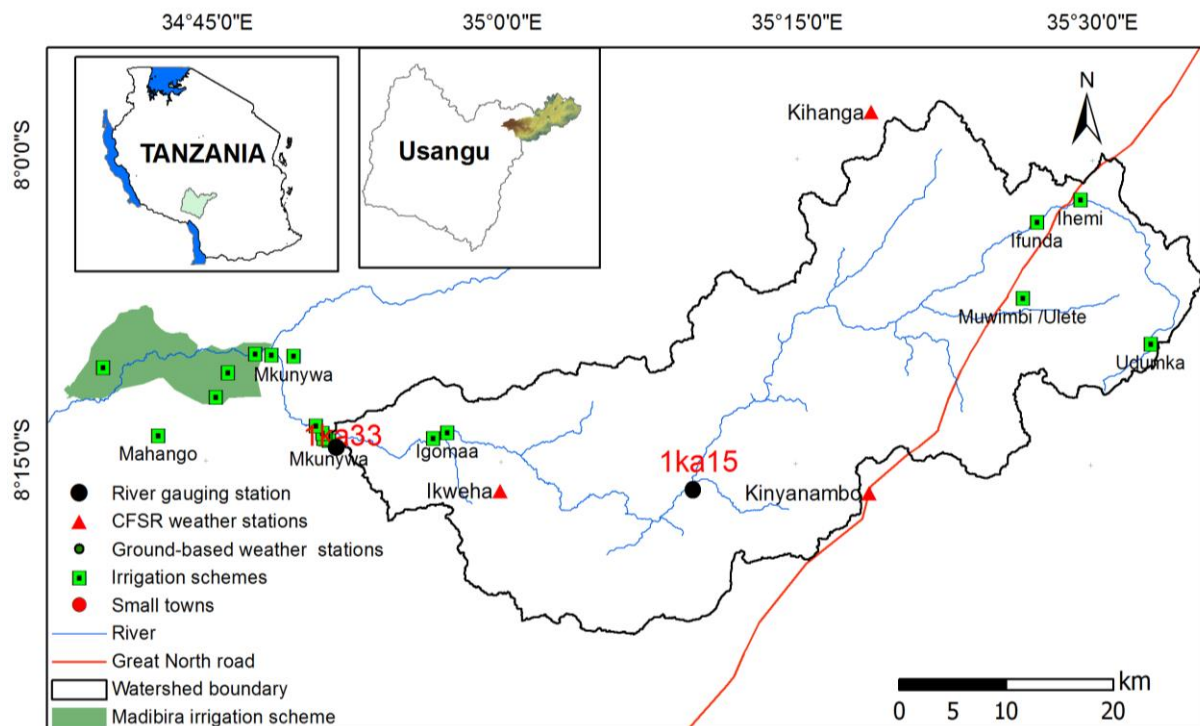


Figure 29: Location of Ndembera watershed showing major farm and irrigation schemes

4.2.2 The description of SWAT model

SWAT is a physically based, basin-scale, continuous-time, computationally efficient, spatially distributed model developed for the USDA Agricultural Research Service (ARS) that operates on a daily time step (Gassman *et al.*, 2007; Shawul *et al.*, 2013). It was developed to predict the impacts of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and

management conditions over long periods of time (Neitsch, 2009). The impact of climate and vegetation change on water quality or other variables of interest, as well physical processes such as water flows in soil and groundwater can be quantified in SWAT model (Arnold *et al.*, 2009; Neitsch, 2009). Hydrologic cycle simulated in the SWAT model is based on the water balance equation (11) (Arnold *et al.*, 2009).

$$SW_t = SW_o + \sum_{i=1}^t (R_{\text{day}} - Q_{\text{surf}} - E_a - W_{\text{seep}} - Q_{\text{gw}}) \quad (11)$$

where SW_t is the final soil water content (mm H₂O), SW_o is the initial soil water content on day i (mm H₂O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H₂O), Q_{surf} is the amount of surface runoff on day i (mm H₂O), E_a is the amount of evapotranspiration on day i (mm H₂O), W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H₂O), and Q_{gw} is the amount of return flow on day i (mm H₂O).

The rainfall is a major process that input water into the watershed system. This rainfall is partitioned into the surface runoff (Q_{surf}), evapotranspiration (E_a), water moving to vadose zone (W_{seep}) and the amount of water that is released to the streams as the return flows (Q_{gw}). Therefore, the amount of water in the soil at any time of the day (SW_t) is the function of the initial soil water content on day (SW_o) plus the retained amount of rainfall after being partitioned into the other components. The partition of rain water into different water balance components and movement of water in the land phase hydrological cycle during SWAT simulation is presented in Fig. 30.

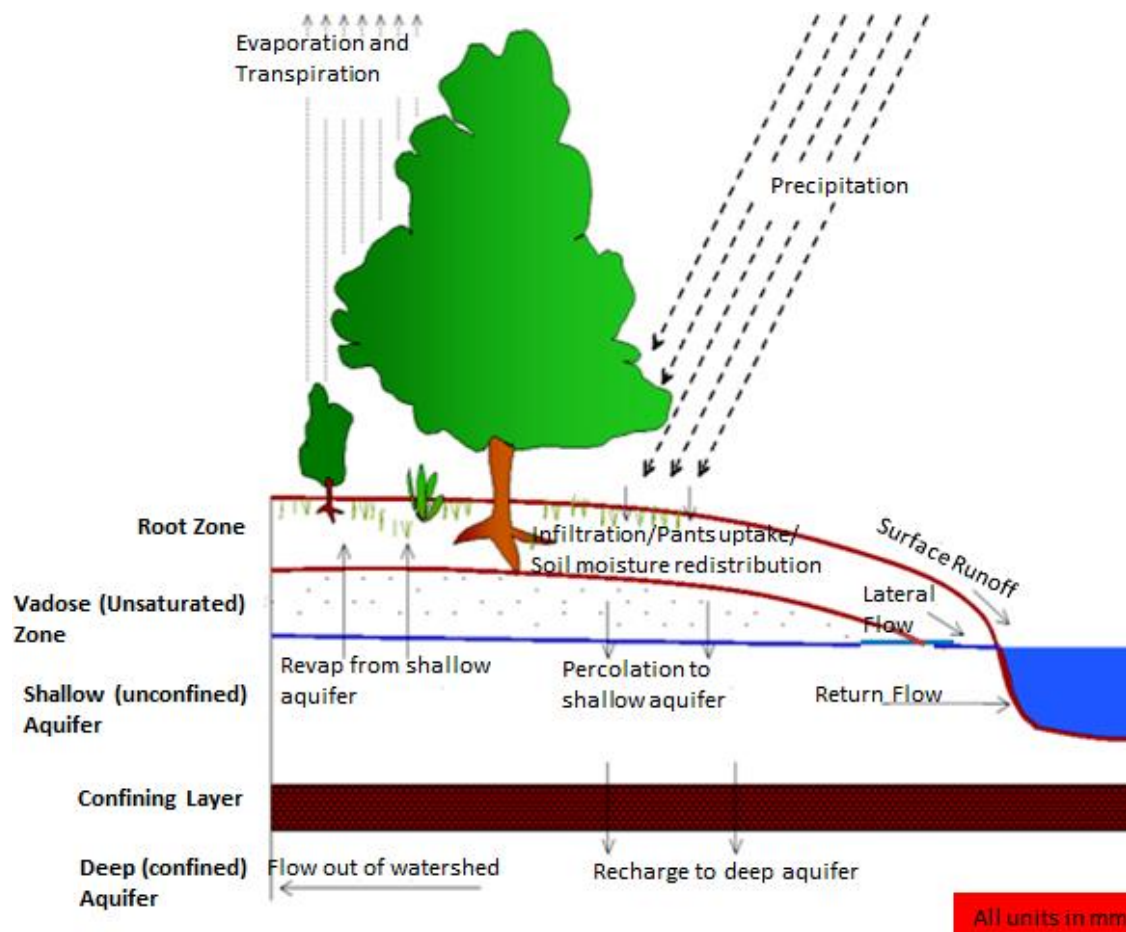


Figure 30: Water balance components and movement of water in the land phase hydrological cycle during SWAT simulation (Source: After Arnold et al., 2009)

4.2.3 Preparation of the ArcSWAT model inputs

The input data for SWAT model (soil, land use, slope and weather data) were pre-processed in ArcMap 10.1 environment to obtain the data format required by ArcSWAT12 database. The STRM 30m Digital Elevation Model (DEM) of the study area (Fig. 31) was downloaded from the USGS database at <https://earthexplorer.usgs.gov/>. The DEM was used for delineating the study area's watershed and stream networks. The slope map (Fig. 32) was derived from the DEM using the Spatial Analyst tool.

Soil data in Fig. 33 was downloaded from the FAO Harmonized global soils database at http://www.waterbase.org/download_data.html. The watershed boundary was used to extract the soil data from the FAO soil database of the African soils slice. The attributes of these soils in Fig. 33 were updated using a "usersoil" table from the MapWindow SWAT12

database due to the fact that the “usersoil” table of ArcSWAT12 soil database contains USA soils only.

The area in percentage of soils of the watershed shown in Fig. 33 was about 48.8% Dystric Nitrosols, 24.5% Humic Gleysol, 21.8% Chromic Cambisol, 4.3% Orthic Acrisol and 0.7% Eutric Planasol. For the slope map (Fig. 32), large areas (50.6%) constitute the land areas on 6-16 percent slope. The rest of the areas are distributed around the areas found between 0-6 and >16 percent slopes which occupy about 37.3% and 12.1% of the total study area, respectively.

The baseline land use/cover map of 2013 (Fig. 34) was prepared by classifying Landsat images obtained from three path and rows (path168/row066, path169/row065 and path169/row066). The 2020 land use/cover of the Ndembera River watershed (Fig. 35) was extracted from the 2020 land use/cover of Usangu Catchment (Hyandye and Martz, 2017). This 2020 land use/cover was predicted using the Markov Chain and Cellular Automata models.

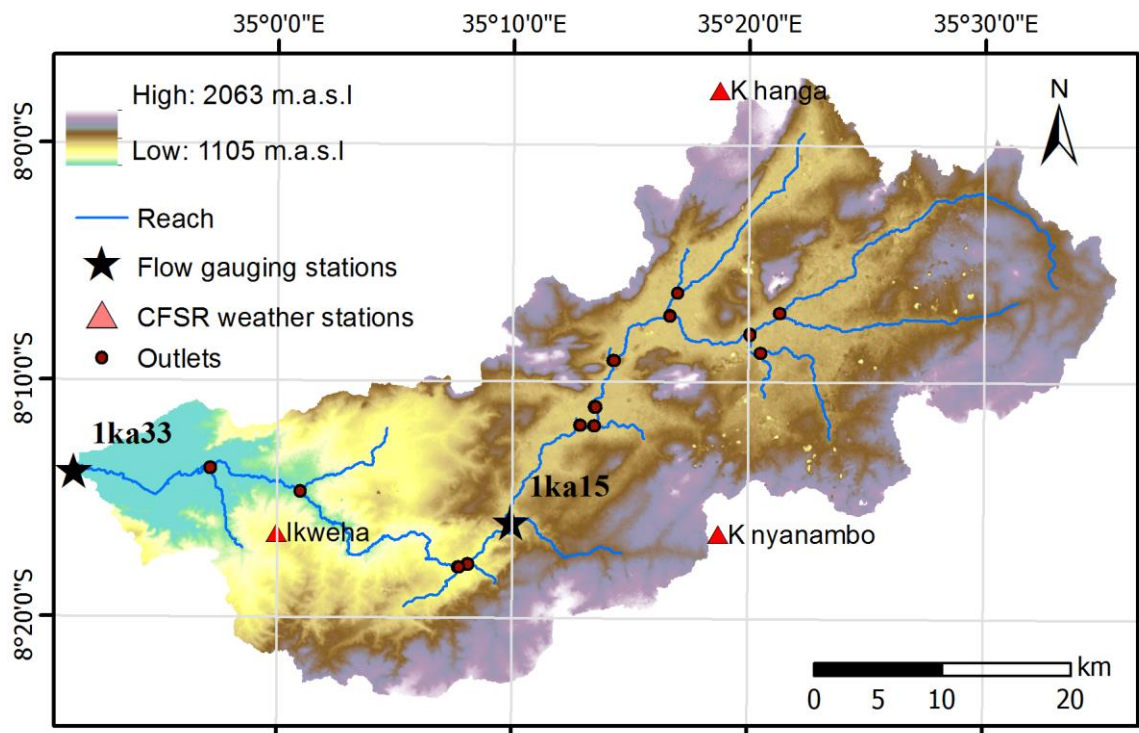


Figure 31: DEM of Ndembera River Catchment. The watershed was delineated using the 1ka33 gauging station at the most downstream outlet

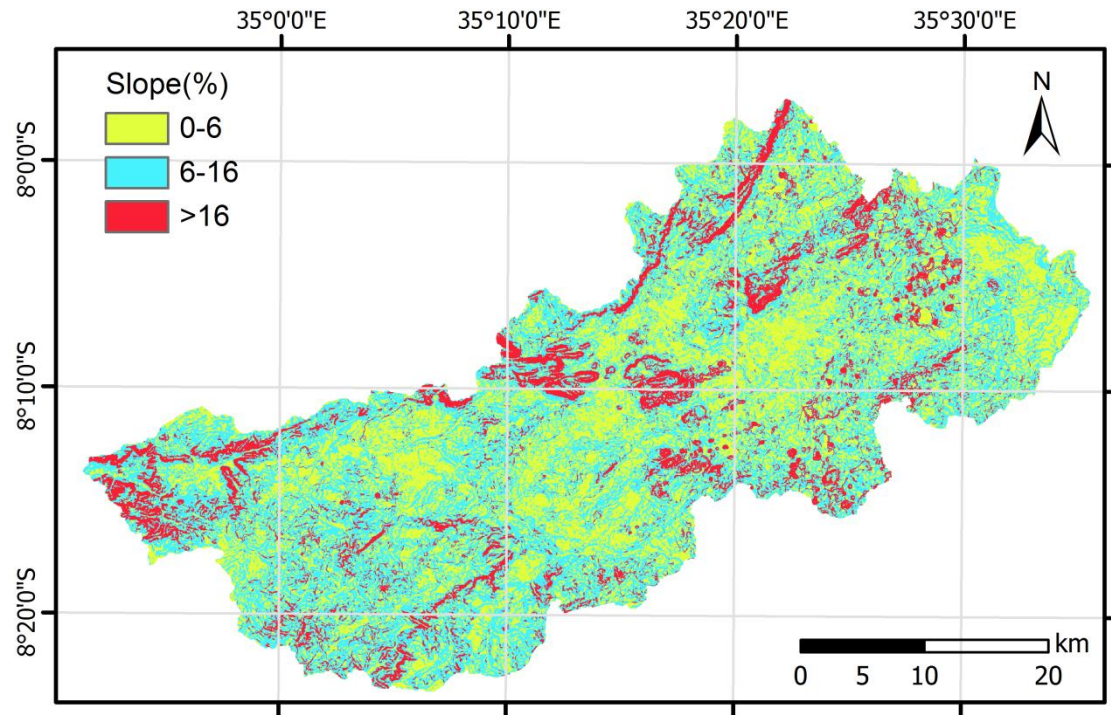


Figure 32: Slope map of Ndembera River Catchment

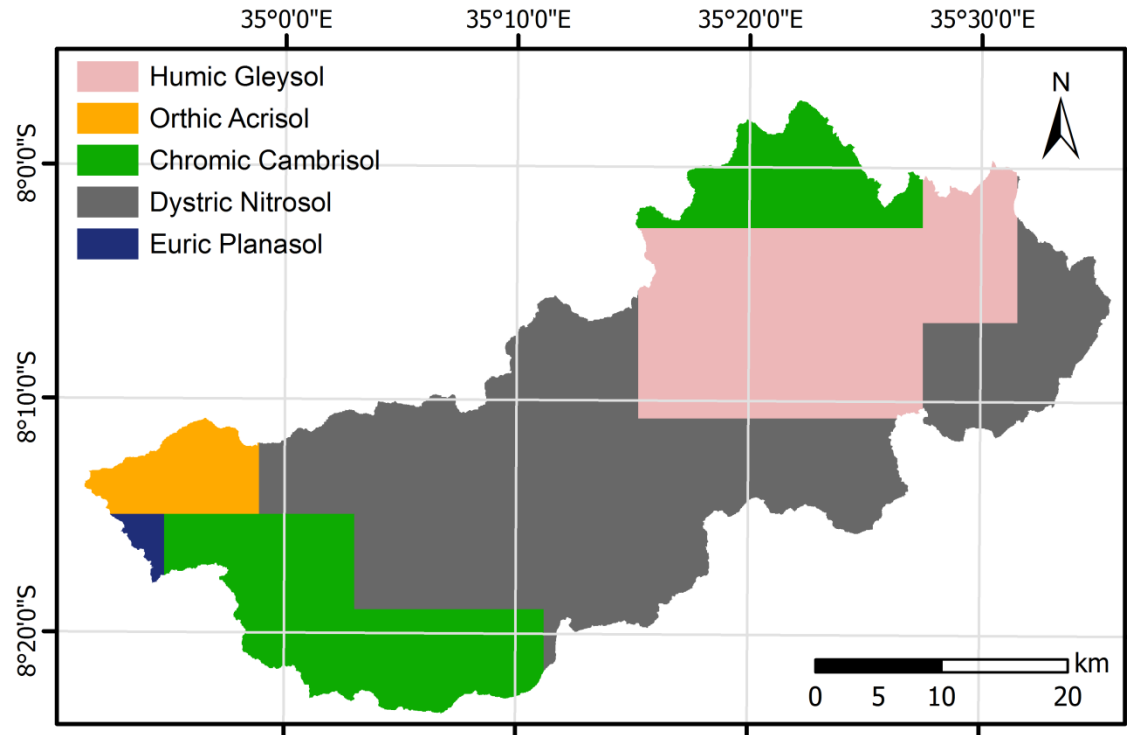


Figure 33: Ndembera River Catchment soil types

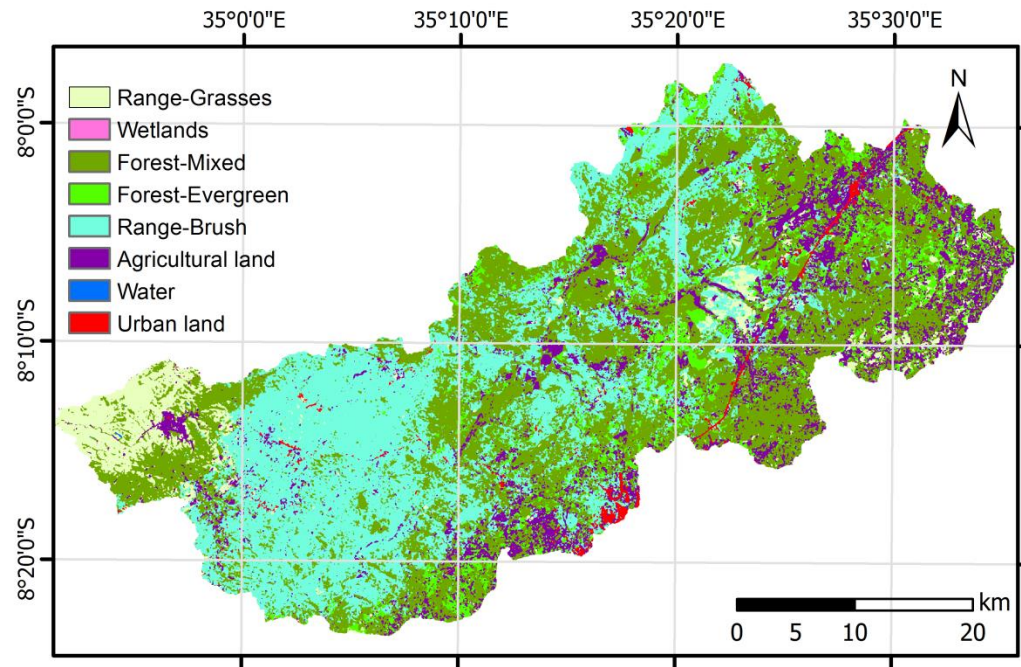


Figure 34: SWAT Land Use types (2013) of Ndembera River Catchment

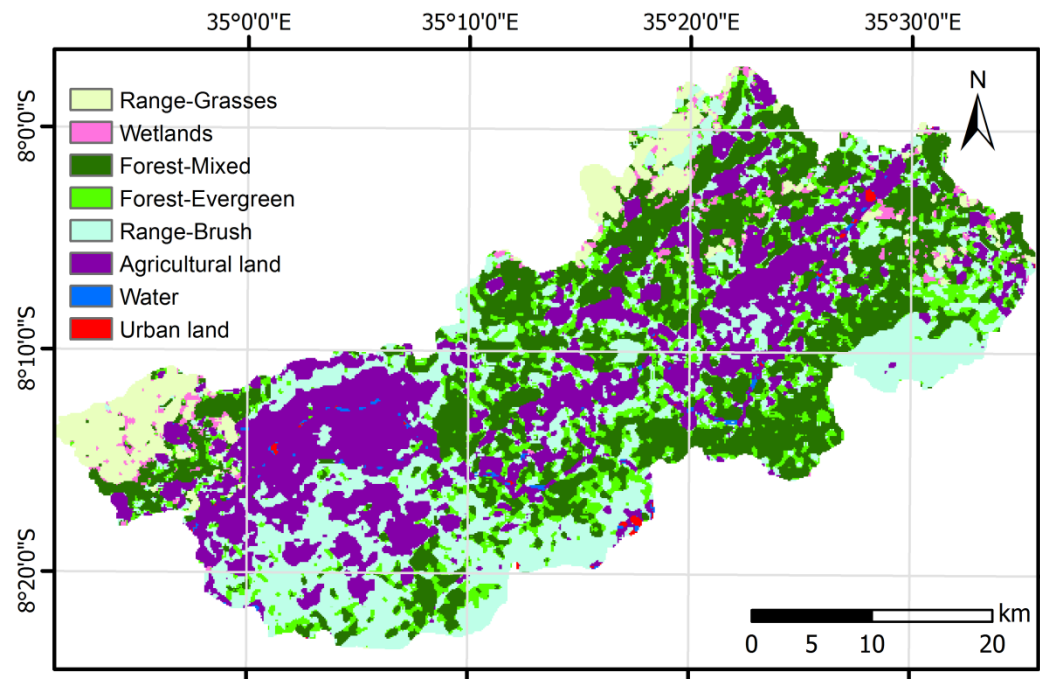


Figure 35: The 2020 land use/cover of Ndembera River Catchment

Weather data was obtained from the ground-based weather gauging station (Iringa Maji) and the Climate Forecast System Reanalysis (CFSR) global weather data for SWAT. The Rufiji Basin Water Board (RBWB) provided the ground-based gauging stations data, while the

CFSR weather data were downloaded from <http://globalweather.tamu.edu/>. Since the three operational ground-based weather stations in Usangu Catchment, namely, Matamba, Iringa Maji and Igawa station were located outside Ndembera watershed (Fig. 29), and Ndembera Auto met station located within the Ndembera watershed has not functioned since 2008, it was necessary to use CFSR global rainfall data. This CFSR data was obtained for Ikweha, Kihanga and Kinyanambo stations (Fig. 29). The CFSR data often overestimate rainfall (Worqlul *et al.*, 2014); hence, Iringa Maji station data, a nearby weather station which had daily series data from 1962 to 2013, were used to perform bias correction of the CFSR precipitation data. The bias correction of the CFSR rainfall data was done through minimizing the annual volume difference between the CFSR and the gauged data using the Solver Excel tool. The two datasets covered the same time window (1999-2013). The bias corrected and uncorrected CFSR data graphs for Kihanga station are compared with the observed data in Fig. 36. The correlation between bias-corrected and observed data was 0.9.

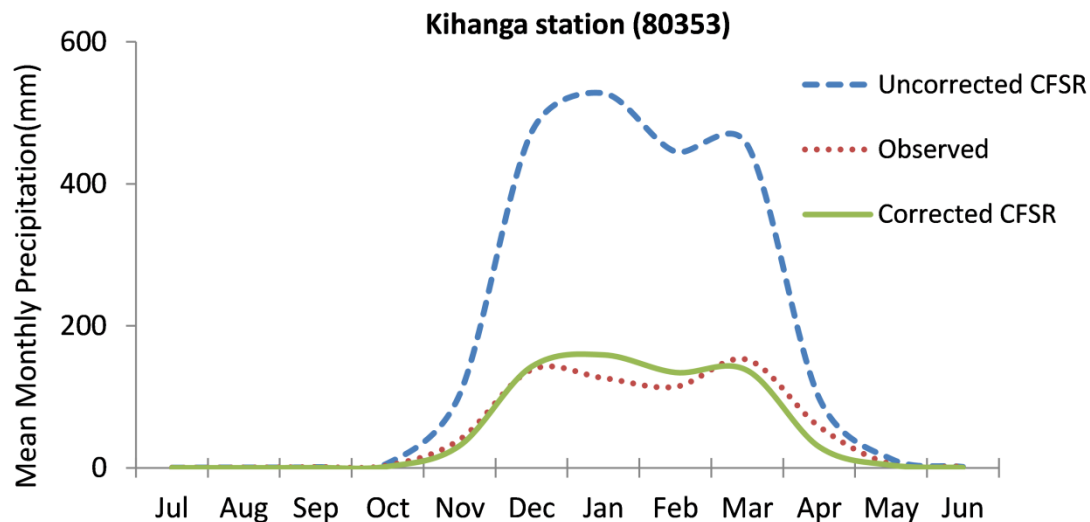


Figure 36: Climate Forecast System Reanalysis rainfall data before and after bias correction

The discharge data for model calibration and validation period (2000-2010) for Ndembera River at gauging station (1ka33) was obtained from the Rufiji Basin Water Board. Two major challenges were encountered. Firstly, the data series had gaps of up to six months, and sometimes for more than a year, as they were observed in 1998-1999. Secondly, the data series had ambiguous data units. It is acknowledged that data at 1ka33 were not of good quality due to poor gauge reading (personal communication). In addition, during our visit to the station in the dry season, we found out that the water flow was below the gauge, meaning

that, in the dry season, the water discharge is not captured. During data processing, the ambiguous data was deleted. Then, the data from the upstream station 1ka15 (Fig. 31) was used to fill data gaps at station 1ka33 for the period from 2000 to 2010 using the simple interpolation and linear regression methods (Gyau-Boakye and Schultz, 1994; Koch and Cherie, 2013).

4.2.4 SWAT Model set-up and parameterization

The whole watershed was divided into 29 sub-basins. This study used a stream generation threshold area of 3410 hectare (34 km²) during the process of watershed and streams delineation. A total of 411 and 470 hydrological response units (HRU) were generated for the baseline and future land use/cover scenarios, respectively. The general sub-basin parameters such as initial leaf area index (LAI_INI), plants potential heat units (PHU_PLT) and curve numbers (CN_2) were updated for the respective land covers. The CN_2 was updated by adopting the curve number values for cultivated agricultural lands which considers the type of land use/cover, tillage practices, hydrologic condition and hydrologic soil group (Neitsch *et al.*, 2002). Management operations for specific land uses such as agricultural lands were scheduled based on the growing calendar used by farmers in the watershed (Table 14). The crops were auto-irrigated and auto-fertilised due to lack of reliable data on the way farmers use their water abstraction permits to irrigate crops. Furthermore, irrigation from surface or groundwater in Usangu catchment is used to supplement rainfall. Therefore, it is hard to quantify the exact amount of annual water abstractions for irrigation. Similarly, the amount and types of fertilizers applied by each farmer in the catchment is not well documented by authorities.

The potential evapotranspiration was estimated using the Hargreaves method which requires less weather data input, that is, temperature (Hargreaves and Samani, 1982; Cherie and Koch, 2013). The runoff was estimated using the curve number method. Following this initial parameterization, the model was tested by running it using weather data from 1999-2001 before its final semi-automatic calibration.

Table 14: Crops growing calendar in Usangu Catchment in a hydrological year

	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Cereal and Grains												
Paddy(Rice)												
Maize												
Oil seeds (sunflower & groundnuts)												
Vegetables												
Onions												
Others (Tomatoes, vegetables, potatoes)												
Legend												
Sowing seeds												
Farms Preparations												
Trans-planting												
1 st weeding												
2 nd weeding												
Mid-season												
Harvest												
Mixed activities												

Note: Hydrological year starts in November and ends in October of the following year. Activities related to tomatoes, vegetables, and sweet potatoes vary from one location to another.

4.2.5 SWAT model calibration and validation

River discharge data of 1999 to 2006 and 2007 to 2010 from the 1ka33 gauging station was used to calibrate and validate the SWAT model, respectively. The calibration and validation were accomplished using a semi-automatic Calibration and Uncertainty Programme; SWAT-CUP SUFI-2 (Arnold *et al.*, 2012). A warm-up period of three years (1999-2001) was used for model initialization during model calibration. The calibration process was preceded by the sensitivity analysis of the parameters that control the observed river flows. The sensitivity analysis considered the range of parameters suggested by Holvoet *et al.* (2005). Twenty-three (23) parameters pre-selected during manual calibration were used in the SWAT-CUP SUFI2 to run one thousand simulations. Nineteen (19) influential parameters of the stream flow were identified for model calibration (Table 15), whereby the sensitivity was evaluated using the t-statistic (t-stat) and p-values. The calibration process involved a logical adjustment of the SWAT parameters within their acceptable ranges based on the knowledge of watershed's conditions.

Table 15: Parameters sensitive to streamflow, their default range, fitted value during calibration and final values used in SWAT model for streamflow simulations

Parameter	Description	SUFI2 fitted value	Default SWAT range	Final value in SWAT Model
v__SURLAG.bsn	Surface runoff lag time (days)	20.76	0.05-24	20.76
v__ESCO.bsn	Soil evaporation compensation factor	0.83	0-1	0.83
a__GWQMN.gw	Threshold depth of water in the shallow aquifer for return flow to occur (mm H ₂ O)	217.08	0-5000	1217.08
a__GW_REVAP.gw	Groundwater “revap” coefficient	0.03	0.02-0.2	0.05
a__REVAPMN.gw	Threshold depth of water in the shallow aquifer for “revap” to occur (mm H ₂ O)	236.07	0-1000	986.07
v__ALPHA_BF.gw	Baseflow alpha factor (days)	0.83	0-1	0.83
v__SHALLST.gw	Initial depth of water in the shallow aquifer	1263.00	0-5000	1263.00
v__RCHRG_DP.gw	Deep aquifer percolation fraction	0.63	0-1	0.63
v__GW_DELAY.gw	Groundwater delay (days)	18.25	0-500	18.25
v__CH_N2.rte	Manning’s “n” value for the main channel	0.11	-0.01 – 0.3	0.11
v__EPCO.hru	Plant uptake compensation factor	0.50	0-1	0.50
a__OV_N.hru	Manning’s “n” value for overland flow	28.86	0.01-30	28.86
a__CANMX.hru	Maximum canopy storage (mm H ₂ O)	10.78	0-100	10.78
a__SLSUBBSN.hru	Average slope length (m)	40.45	10-150	131.91
a__HRU_SLP.hru	Average slope steepness (m/m)	0.44	0.3-0.6	0.47
a__SOL_AWC().sol	Available water capacity of the soil layer (mm H ₂ O/mm soil)	-0.06	0-1	0.04
a__SOL_K().sol	Saturated soil hydraulic conductivity (mm/h)	21.37	0-2000	39.02
a__CH_K1.sub	Effective hydraulic conductivity in main channel alluvium (mm/h)	85.56	0-300	85.56
a__CN2.mgt	Initial SCS runoff curve number for moisture condition II	-1.87	35-98	83.13

a__ means absolute; a given value is added to the existing parameter value during the calibration

v__ means replace; the existing parameter value is to be replaced by a given value during the calibration

4.2.6 SWAT model performance evaluation

The model performance in predicting the catchment conditions was evaluated using the statistical analysis parameters such as coefficient of determination (R^2) and Nash-Sutcliffe efficient (NSE). In addition, the percentage bias (PBIAS) and graphical methods (discharge hydrograph) were also considered. The model uncertainty analysis was carried out using r-factor and p-factor (Arnold *et al.*, 2012). The r-factor refers to the thickness of the 95% prediction uncertainty (95PPU) envelope, while the p-factor is a percentage of observations covered by the 95% prediction uncertainty.

Theoretically, the value for p-factor ranges between 0 and 100%, while that of r-factor ranges between zero and infinity. A p-factor of 1 and r-factor of zero is a simulation that exactly corresponds to measured data. The degree to which model results are away from these numbers can be used to judge the strength of the model calibration. For p-factor, a value of >70% and r-factor of around 1 are suggested for discharge calibration (Abbaspour, 2015).

4.2.7 Calibration and validation of future climate data

The Near-term (2010-2039) climate scenario of precipitation and temperatures was generated from the 29 GCMs using the procedures described in the Guide for Running AgMIP Climate Scenario Generation Tools with R (Hudson and Ruane, 2013). These GCMs were sourced from the Coupled Model Intercomparison Project 5 (CMIP5). The GCMs included ACCESS1-0, bcc-csm1-1, BNU-ESM, CanESM2, CCSM4, CESM1-BGC, CSIRO-Mk3-6-0, GFDL-ESM2G, GFDL-ESM2M, HadGEM2-CC, HadGEM2-ES, Inmcm4, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC5 and MIROC-ESM-CHEM. Others were MPI-ESM-LR, MPI-ESM-MR, MRI-CGCM3, NorESM1-M, FGOALS-g2, CMCC-CM, CMCC-CMS, CNRM-CM5, HadGEM2-AO, IPSL-CM5B-LR, GFDL-CM3, GISS-E2-R and GISS-E2-H. The models were provided by Sokoine University of Agriculture, Tanzania and the National Aeronautics and Space Administration Goddard Institute for Space Studies (NASA-GISS), USA. The Simple Delta Method was used for statistical downscaling of the GCMs. This method preserves the observed patterns of temporal and spatial variability from the gridded observations (Hamlet *et al.*, 2010).

The statistical downscaling of the 29 GCMs involved the calculation of the change factor (the ratio between a mean value, in the future, and historical run) using the delta change algorithm

that was acquired together with the CMIP5-GCMs (Fig. 37). This change factor was then applied to the observed time series (1980-2009) to transform it into a time series representing the future climate. The 2010-2039 climate scenario was analysed under the Representative Concentration Pathway 8.5. Greenhouse Gas Emission scenario. This concentration pathway is characterized by increasing Greenhouse gases emissions over time, a representative of scenarios leading to high Greenhouse gases concentration levels (Chaturvedi *et al.*, 2012).

The sub-selection of the five representative GCMs for Hot/Wet, Hot/Dry, Cold/Wet, Cold/Dry and Middle (Ensemble mean) future climatic conditions was based on a scatter diagram approach (Fig. 38) The diagram represented the changes in mean monthly temperatures against the percentage in mean monthly change in future precipitation from the baseline scenario. The GCM falling close to the median of each quadrant was selected according to Subash *et al.* (2016). The GCMs selected for each weather station in the watershed (Table 16) were averaged to obtain a site-specific GCMs-derived climate data.

The mean GCMs-derived precipitation and temperatures were validated by comparing them with the observed historical station data 1980 to 2009 and 2010 to 2013. The validation involved a graphical and statistical analysis. The statistical analysis included the Mean error (ME), correlation (R), Median, Mean and Standard deviation (SD).

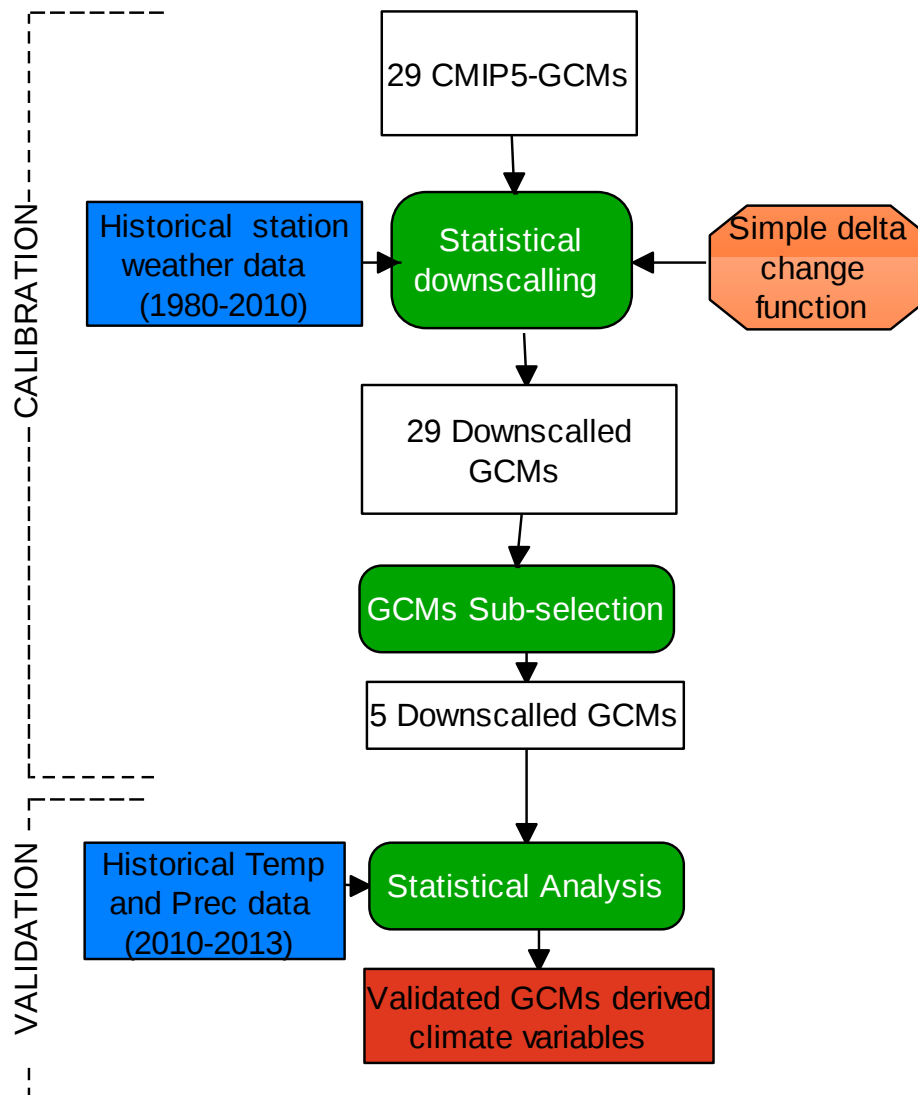


Figure 37: Schematic diagram showing the workflow to generate future climate variables in the present study

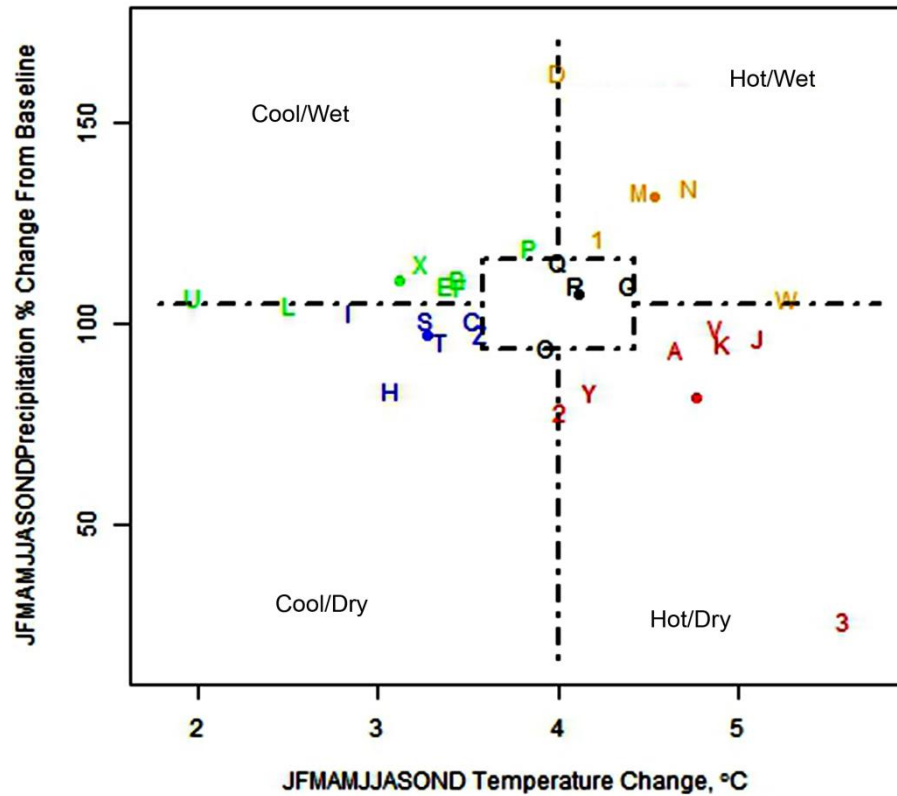


Figure 38: Temperature-and-Precipitation change scatter diagram for Kinyanambo station (83353)

Table 16: Selected CMIP5-GCMs for forcing the SWAT model

Station ID	Local name	Lat	Long	Altitude	GCM ID	GCM Name	Future condition
80353	Kihanga	-7.96	35.31	1589	D	CanESM2	Hot/wet
					B	bcc-csm1-1	Cool/Wet
					S	MRI-CGCM3	Cool/Dry
					2	GISS-E2-R	Hot/Dry
					R	MPI-ESM-MR	Middle
83353	Kinyanambo	-8.27	35.31	1803	M	IPSL-CM5A-LR	Hot/wet
					X	CNRM-CM5	Cool/Wet
					S	MRI-CGCM3	Cool/Dry
					A	ACCESS1-0	Hot/Dry
					R	MPI-ESM-MR	Middle
83350	Ikweha	-8.27	35.00	1427	M	IPSL-CM5A-LR	Hot/wet
					F	CESM1-BGC	Cool/Wet
					S	MRI-CGCM3	Cool/Dry
					R	MPI-ESM-MR	Hot/Dry
					Q	MPI-ESM-LR	Middle

4.2.8 Simulation of the impacts of future land use/cover, climate and land management practices on water balance

The 2020 land use/cover of the Ndembera River watershed was introduced in a calibrated SWAT model to replace the baseline land use/cover of 2013. The model was then run to simulate the water balance conditions using the 2020 land use/cover scenario without changing other SWAT input data (weather, soils, and slope). The following assumptions were made: i) land use/cover will change as expected, and ii) the hydrological and atmospheric conditions, soils and slope will remain unchanged over the next decade. The future GCMs-derived climate data was then introduced into the Ndembera SWAT model that had been updated with the 2020 land use/cover. This was done in order to simulate the combined effect of future climate and land use/cover changes on water balance. Lastly, the same SWAT model setup containing the 2020 land use/cover and the 2010-2039 GCMs-derived climate data was used to simulate the impacts of land and water management practices on water balance and streamflow. The practices included terracing and contouring, filter strips, grassed waterways and deep ripper subsoiler tillage. The choice of these management practices was based on the nature of the landscape (slope) and the expected land use/cover and climate changes on water balance in the watershed such as reduced infiltration and increased evapotranspiration.

The effects of the four management practices on water balance were simulated in SWAT by activating the sub-models of the respective management practices. Table 17 shows the parameters and their final values used for water balance simulation under each management practice. These values were applied in the hydraulic response units with agricultural land use only.

Table 17: List of SWAT input parameters and values used for each management practice

Management Practice	SWAT Input Table	Parameters	Parameter description	Value
Filter strips	Management (.Mgt)	FILTERW	Width of the edge of field filter strips (m)	30*
	Operations (.Ops)	FILTER_RATIO	Ratio of field area to filter strip area (unitless).	40
	Operations (.Ops)	FILTER_CON	Fraction of the HRU which drains to the most concentrated ten percent of the filters strip area	0.5
	Operations (.Ops)	FILTER_CH	Fraction of the flow within the most concentrated ten percent of the filter strip that is fully channelized (dimensionless).	0
Grassed waterways	Operations (.Ops)	GWATN	Manning's "n" value for overland flow	0.35
	Operations (.Ops)	GWATL	Grass waterway length (km)	1000
	Operations (.Ops)	GWATW	Average width of grassed waterway (m)	10*
	Operations (.Ops)	GWATD	Depth of grassed waterway channel from top of bank to bottom (m)	1
	Operations (.Ops)	GWATS	Average slope of grassed waterway channel.	HRU Slope×0.75
Terraces and Contour	Operations (.Ops)	TERR_CN	Curve number	62* *
	Operations (.Ops)	TERR_SL	Average slope length (m)	61***
	Operations (.Ops)	CONT_CN	Initial SCS curve number II value	62**
Deep ripper subsoiler	Management (.Mgt)	CNOP	SCS runoff curve number for moisture conditions II	62**

*User defined value based on knowledge from the field, **Adopted from Table 20-1 of runoff curve numbers for cultivated agricultural lands (Arnold *et al.*, 2013), ***Values from the calibrated SWAT model. Other values without the asterisk (*) were default values from the SWAT database.

4.3 Results

4.3.1 Sensitivity analysis results

The top six most sensitive parameters to the river discharge were the groundwater delay factor (GW_DELAY), average slope steepness (HRU_SLP), groundwater "revap" coefficient (GW-REVAP), available water content of the soil (SOL_AWC), average slope length

(SLSUBBSN), and the curve number (CN_2) (Fig. 39). Compared to others, these six parameters showed higher t-Statistic values (≥ 2 to 16) and lower p-values (0 to <0.05). Four parameters (CN_2, SLSUBBSN, SOL_AWC and HRU_SLP) were the surface flow response parameters while two parameters (CH_K1 and CH_N2) were channel response parameters and showed very low sensitivity to the river discharge.

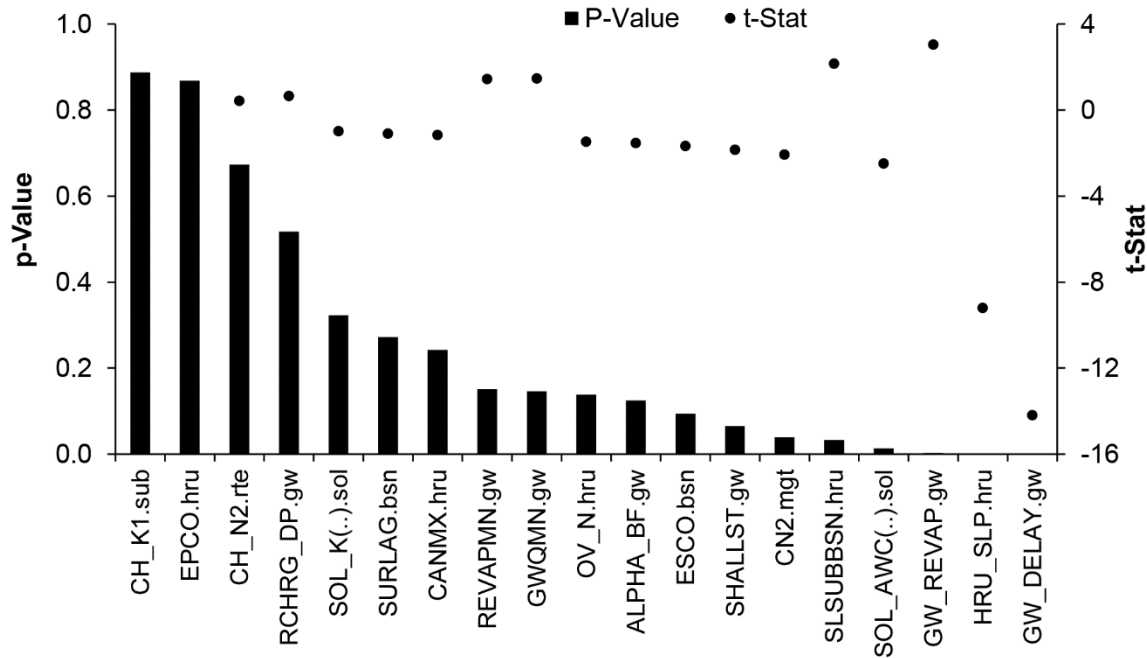


Figure 39: The t-statistic and p-values of the calibrated parameters of Ndembera River watershed

4.3.2 Performance of the SWAT model and Uncertainty Analysis

The coefficients of determination (R^2), the Nash-Sutcliffe efficient index (NSE) and PBIAS values showed that there was a good fit between the observed and the simulated flow both in the calibration and validation period (Table 18). The R^2 for calibration and validation periods were 0.79 and 0.80, respectively. The NSE ranged from 0.78 to 0.76. The differences between the simulated and observed discharge at 1ka33, expressed as the percentage bias (PBIAS) was very small for the calibration and validation period (3.8 and -4.6, respectively).

A comparison between SWAT simulated and observed discharge of the Ndembera River at 1ka33 on monthly time step in Fig. 40a showed a good capture of both ascent and recession of the river hydrograph. The hydrograph matched well with the precipitation rhythm of the

catchment. The peaks of the simulated streamflow appeared to be underestimated both during the calibration and validation periods except in 2010 where the peak flows of simulated flow were greater than the observed flow. Generally, the simulated streamflow from the calibrated model slightly underestimated the actual streamflow during the low flows.

The respective *p*-factor and *r*-factor statistic were 0.63 and 0.61 for the calibration period and 0.48 and 0.65 for the validation period (Table 18). These *p*-factor and *r*-factor that represent model uncertainty are graphically presented by the 95 Percent Prediction Uncertainty band (95PPU) in Fig. 40b. The green shaded area in Fig. 40b is the uncertainty in the simulated daily river discharge quantified by the 95% prediction uncertainty. The 95PPU in Fig. 40b bracketed 63% and 48% of observed flow during calibration and validation periods, respectively. Given the high values for R^2 and NSE and good match hydrographs as well as the *p*-factor and *r*-factor values (*p*-factor ≥ 0.5 and *r*-factor < 1), the model was considered suitable for water balance simulation in this study.

Table 18: SWAT model's calibration and validation statistical analysis results

Parameter	Statistical Values	
	Calibration	Validation
NSE	0.78	0.76
R^2	0.79	0.80
<i>p</i> -factor	0.63	0.48
<i>r</i> -factor	0.61	0.65
PBIAS	3.8	-4.6

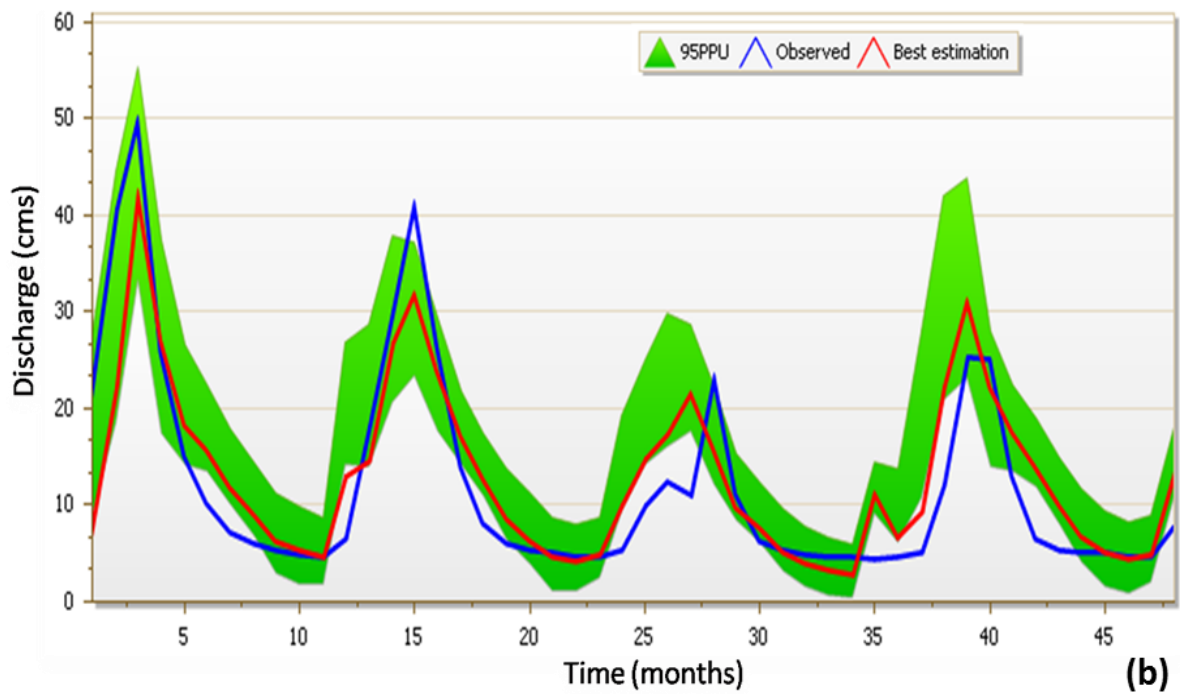
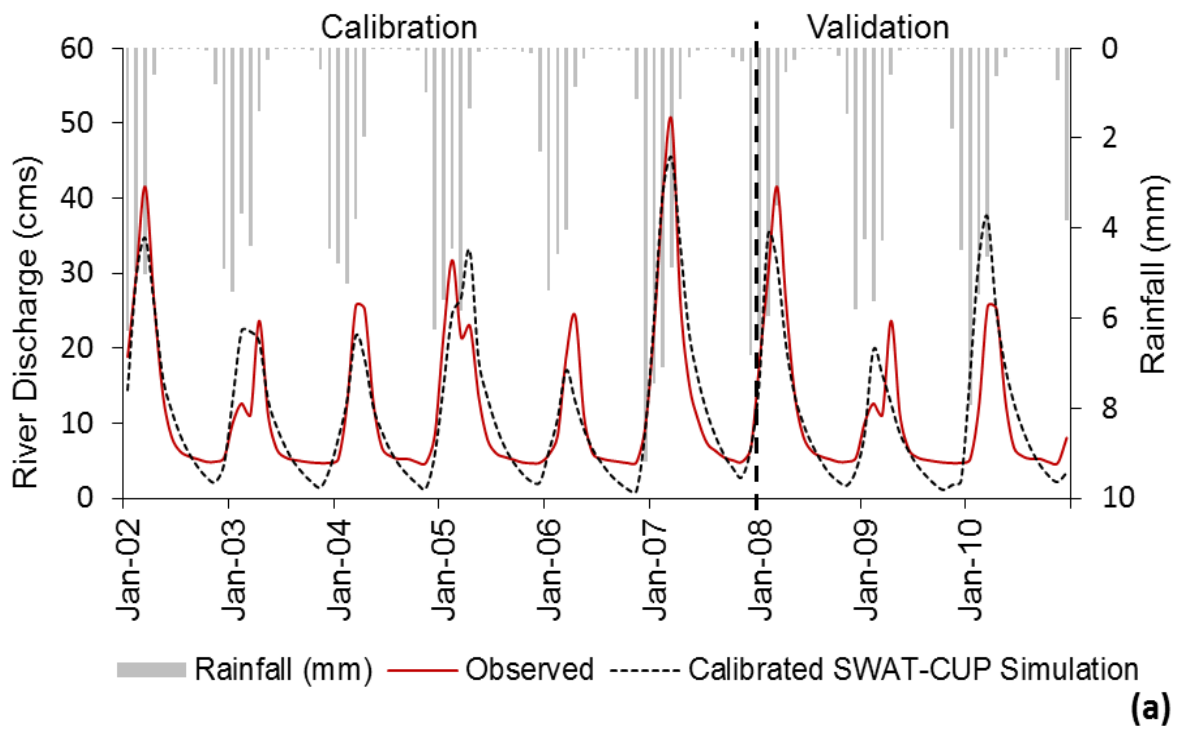


Figure 40: Comparison between simulated and observed monthly discharge of Ndembera River (a) and the 95 Percent Prediction Uncertainty band (b)

4.3.3 Evaluation of the GCMs-derived climate data

The mean monthly precipitation and temperature from the downscaled GCMs for both the baseline and verification periods showed a good match with the observed data (Fig. 41 and Fig. 42). In these figures, the curves of the GCMs-derived climate data captured very well the pattern (peaks and troughs) of the inter-annual variations in the observed data series from the three weather stations. Results in Table 18 depicted good linear relationship between observed and GCM-derived climate data ($R = 0.92$ to 0.99 for precipitation and 0.77 to 0.99 for temperature).

The comparison between observed and GCMs-derived temperature in Fig. 42a&b showed a slight underestimation of GCMs-derived temperature while Fig. 42c indicated an overestimation. The degree to which the GCMs-derived climate variables were underestimated or overestimated were denoted by positive and negative mean error values (ME) in Table 19. Kinyanambo station mean error values were 0.95 and 1.24 for the baseline and verification periods, respectively; while, Ikweha station had negative mean error values of -1.19 and -0.91 , respectively. The mean error values of precipitation from all three weather stations ranged from -0.19 to 0.05 . Generally, the mean error values for both temperature and precipitation were relatively small. In addition, the distribution parameters, the mean, standard deviation (SD) and median of the GCMs-derived climate data were close to those from the observed station data.

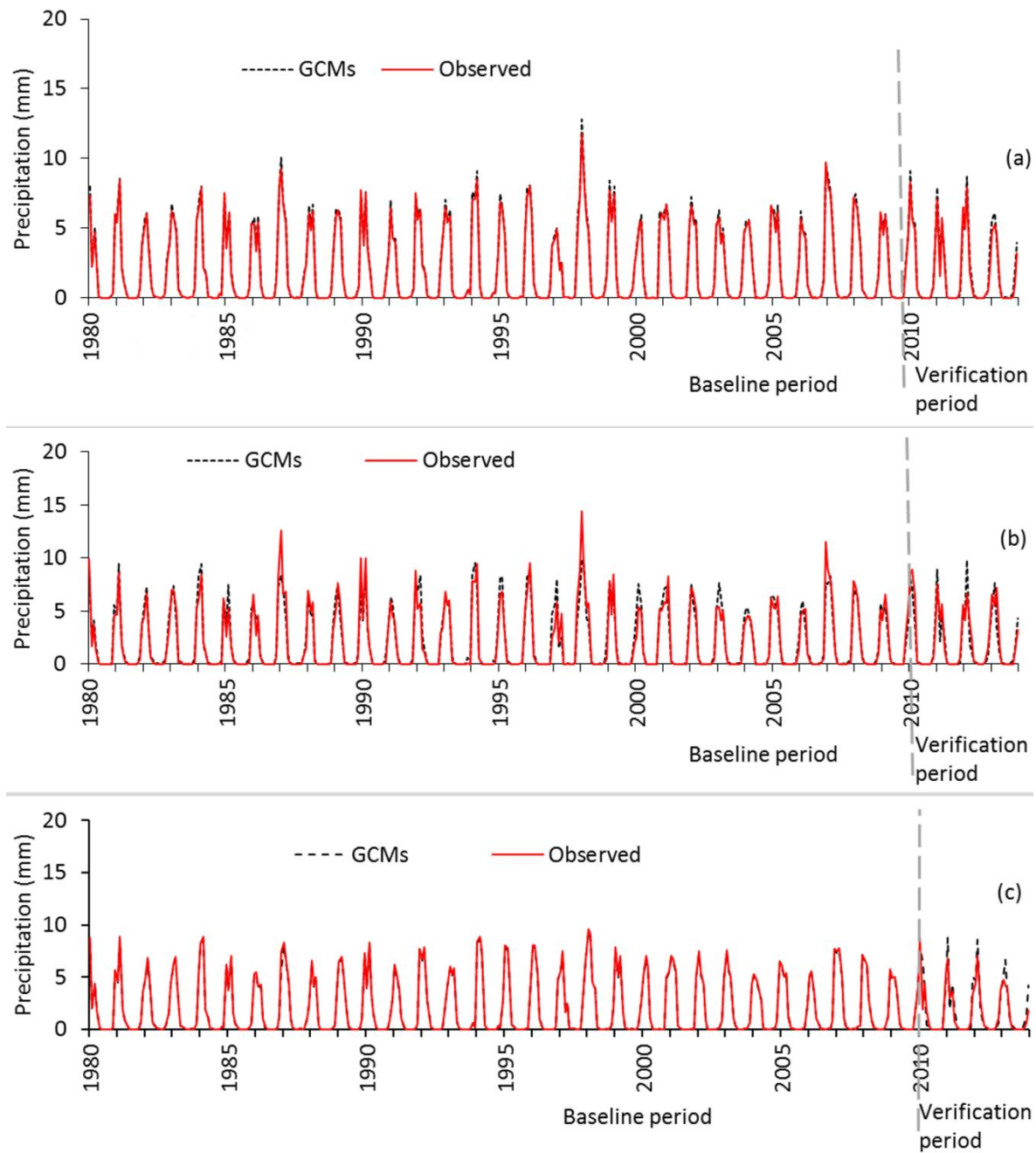


Figure 41: Observed and GCMs-derived mean monthly precipitation for Kihanga the three weather stations (a=Kihanga, b=Ikweha and c=Kinyanambo) during baseline and verification periods

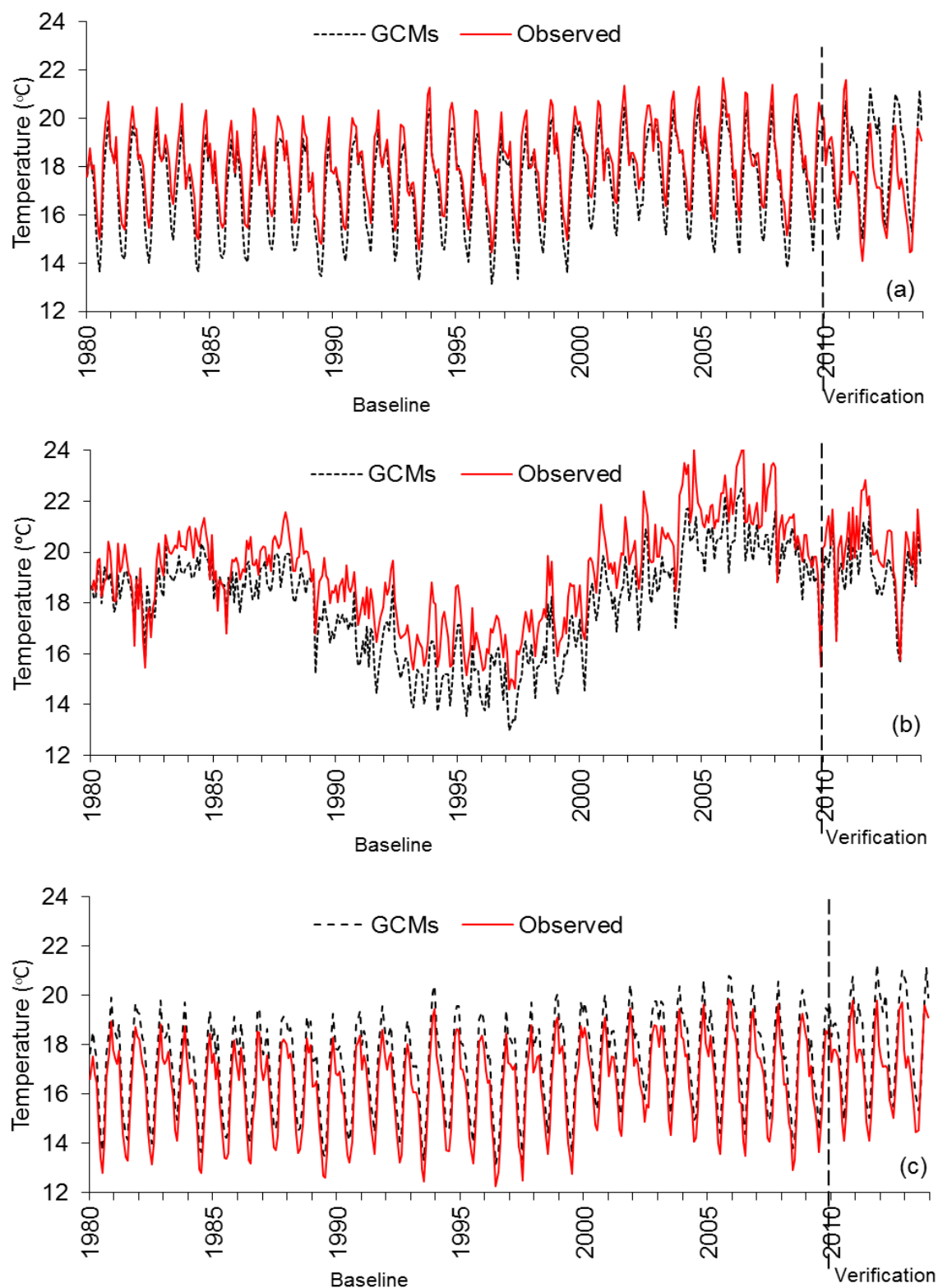


Figure 42: Observed and GCMs-derived mean monthly temperature for the three weather stations (a=Kihanga, b=Ikweha and c=Kinyanambo) during baseline and verification periods

Table 19: Statistical analysis results of the monthly precipitation and temperature for the baseline and verification periods

Station	Parameter	Period	ME	R	Mean		SD		Median	
					GCM	Observed	GCMs	Observed	GCMs	Observed
Kihanga (80353)	Precipitation	Baseline	-0.09	0.99	2.12	2.03	2.80	2.69	0.29	0.28
		Verification	-0.19	0.98	2.00	1.81	2.66	2.48	0.30	0.37
Ikweha (83350)	Temperature	Baseline	-0.79	0.96	17.30	18.10	1.82	1.60	17.65	18.10
		Verification	0.81	0.77	18.32	17.52	1.83	1.71	18.73	17.45
	Precipitation	Baseline	0.05	0.96	2.08	2.02	2.80	2.93	0.27	0.11
		Verification	-0.15	0.92	1.95	2.10	2.72	2.75	0.35	0.28
	Temperature	Baseline	-1.19	0.95	17.95	19.14	2.03	1.99	18.43	19.23
		Verification	-0.91	0.92	19.31	20.22	1.17	1.40	19.36	20.16
Kinyanambo (83353)	Precipitation	Baseline	-0.05	0.99	2.00	2.05	2.67	2.74	0.29	0.30
		Verification	-0.19	0.92	1.86	1.66	2.55	2.22	0.39	0.31
	Temperature	Baseline	0.95	0.99	17.29	16.35	1.82	1.79	17.66	16.70
		Verification	1.24	0.91	18.33	17.09	1.83	1.57	18.72	17.21

4.3.4 Current and future trends of mean climate in the watershed

The annual mean precipitation and mean monthly temperature of the Ndembera watershed for the past three decades (1980 to 2009) showed an increasing trend (Fig. 43a and 44a). The same trend was observed in the near-future period (Fig. 43b and 44b). Whereas the annual mean precipitation increase from 1980-2009 was about 2.4 mm/year (Fig. 43a), that of the near-term period was about 3.2 mm/year (Fig. 44a). Based on the regression equation in Fig. 43b, the watershed annual mean precipitation was shown to be about 801.4 mm/year at the end of 2039. Regarding temperature, the watershed mean monthly temperature changed from 16.8°C in 1980 to about 17.6°C at the end of 2009 (Fig. 44a), an increase of about 0.8°C over the past 30 years. The temperature of the period between 2010 and 2039 are expected to increase by 1.1°C (from 18.1°C in 2010 to 19.2°C in 2039) (Fig. 44b).

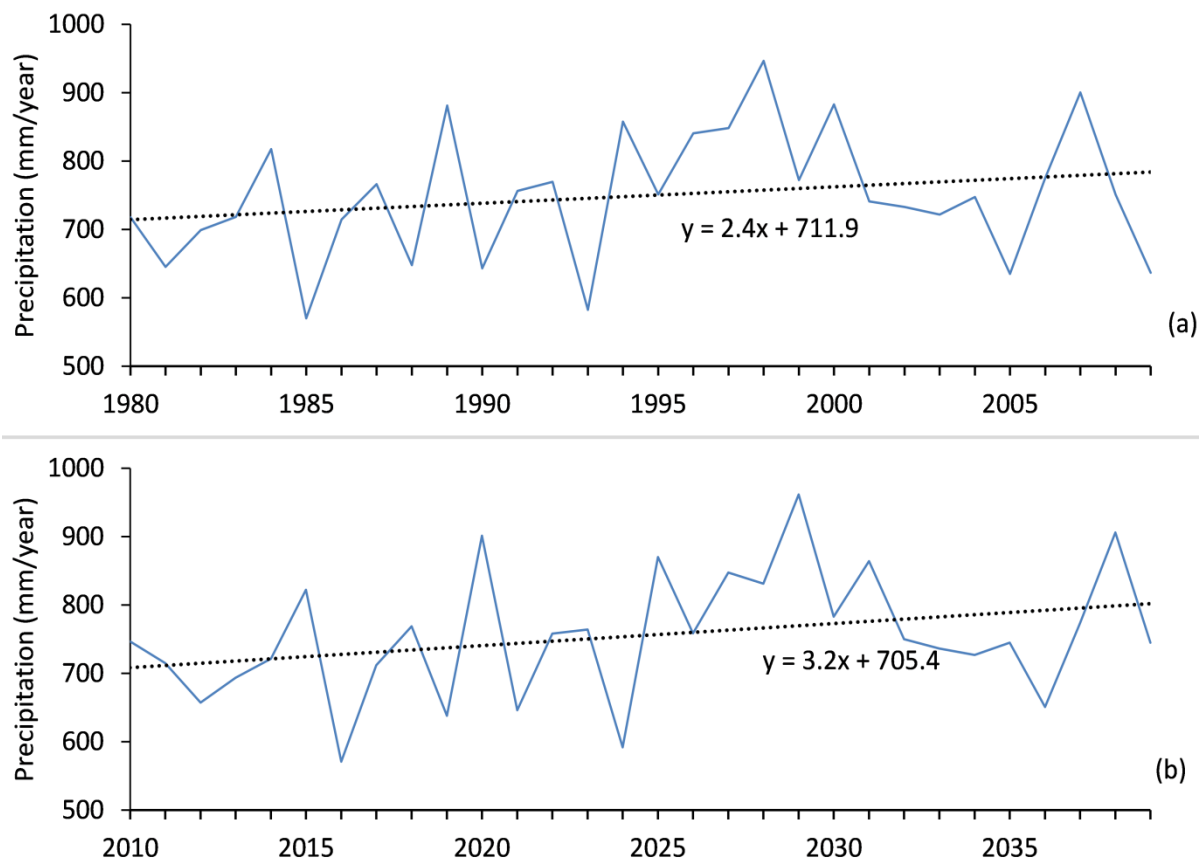


Figure 43: Trend of annual mean precipitation amounts from 1980-2009 (a) and 2010-2039 (b)

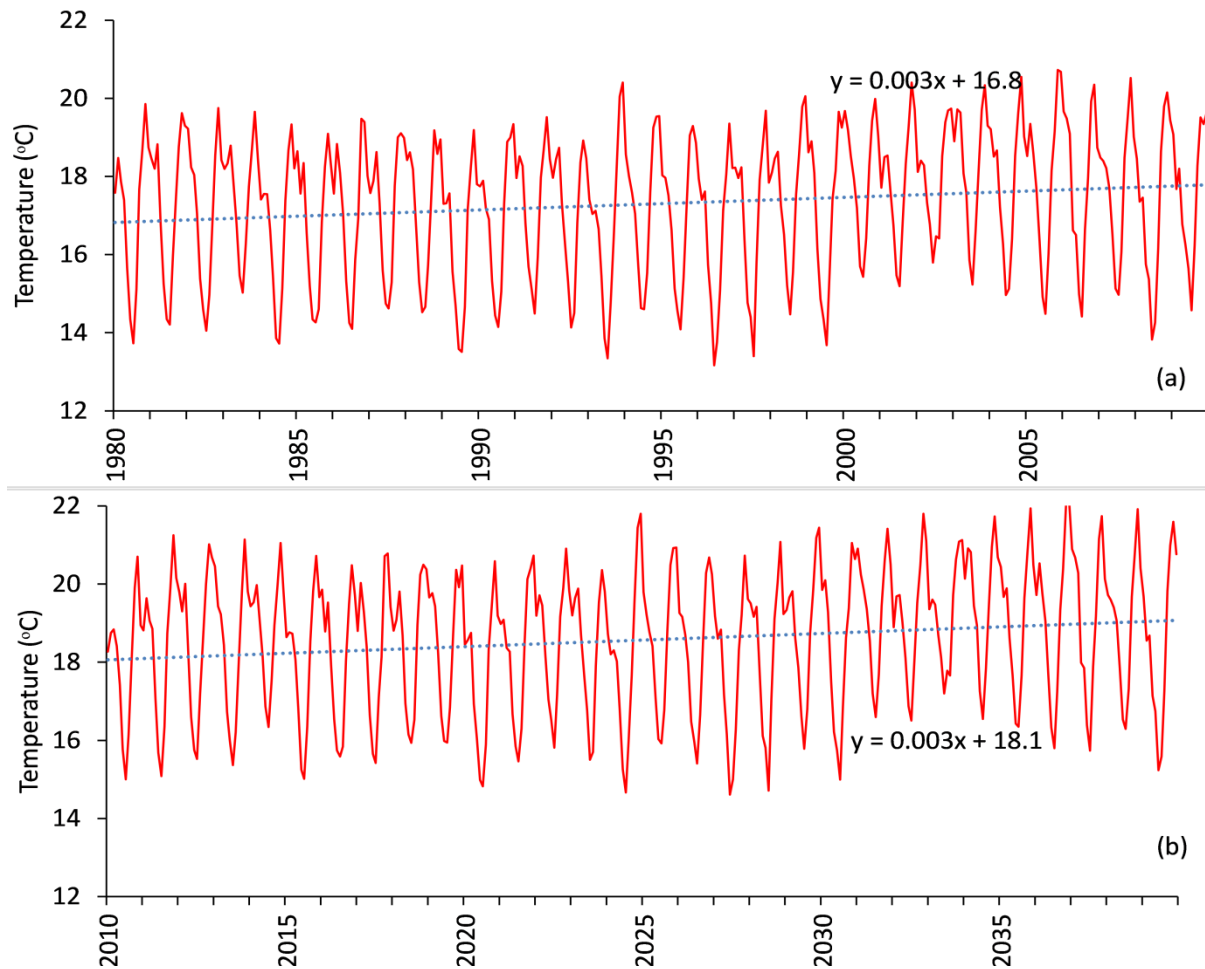


Figure 44: Mean monthly temperature trend from 1980-2009 (a) and 2010-2039 (b)

A comparison of the amount of precipitation for each month averaged over a 30 years period, both in the baseline and near-term periods, showed higher amounts of precipitation in the wet months of January-April in the near-term than in the baseline period (Fig. 45). The change in the amount of precipitation in these months for the two periods ranged from 2-6 mm/month (~2-7%). In the early months of the wet season (November and December), the near-term showed less amounts of precipitation than the baseline period. The precipitation decrease was 6 mm/month (~20%) in November and 4 mm/month (~3%) in December (Fig. 45). The minimum and maximum monthly mean temperature for the watershed were higher in the near-term than in the baseline period throughout the year (Fig. 46). The highest temperature change between the two periods was 1.5°C in November for maximum temperature and 1.4°C in June and July for the minimum temperature.

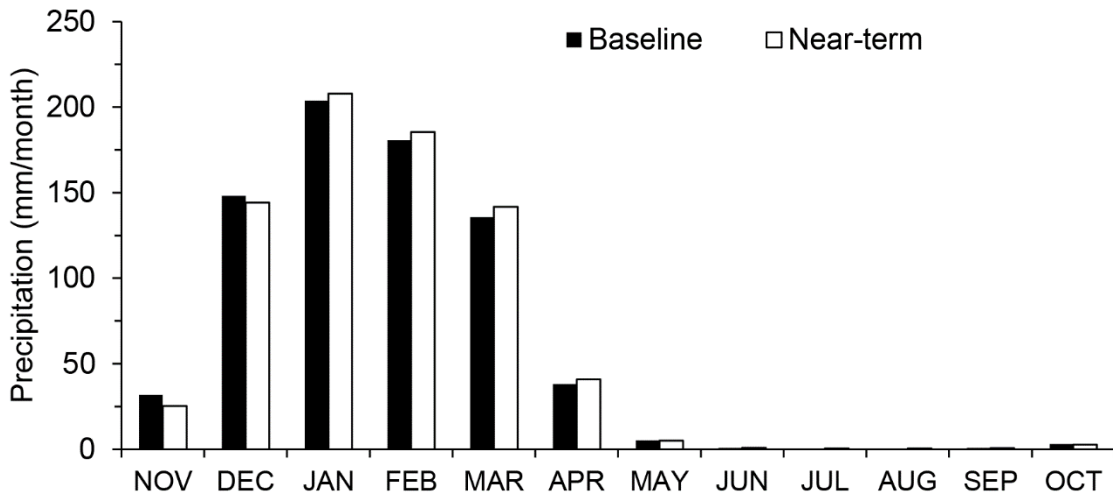


Figure 45: Monthly total precipitation of Ndembera watershed averaged over the whole baseline and near-term periods

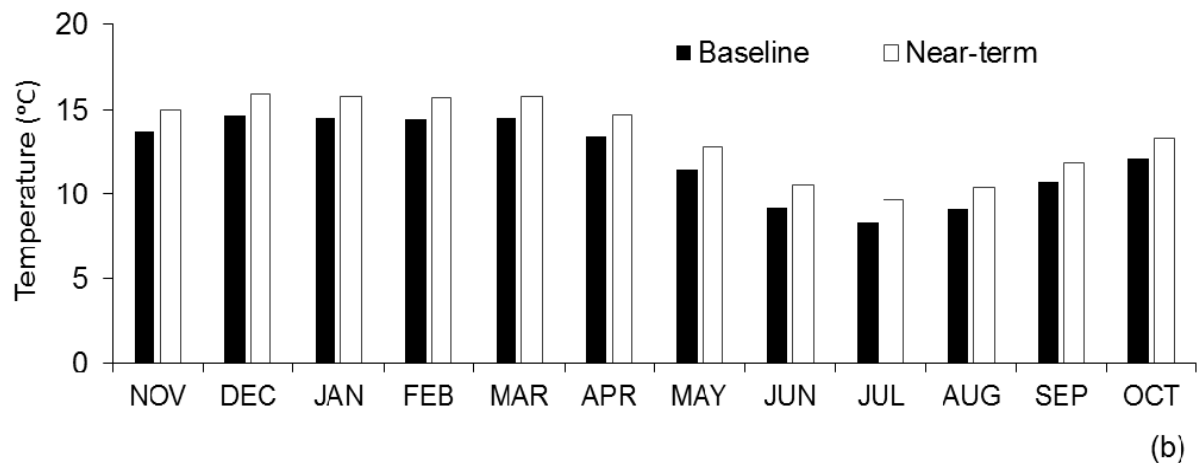
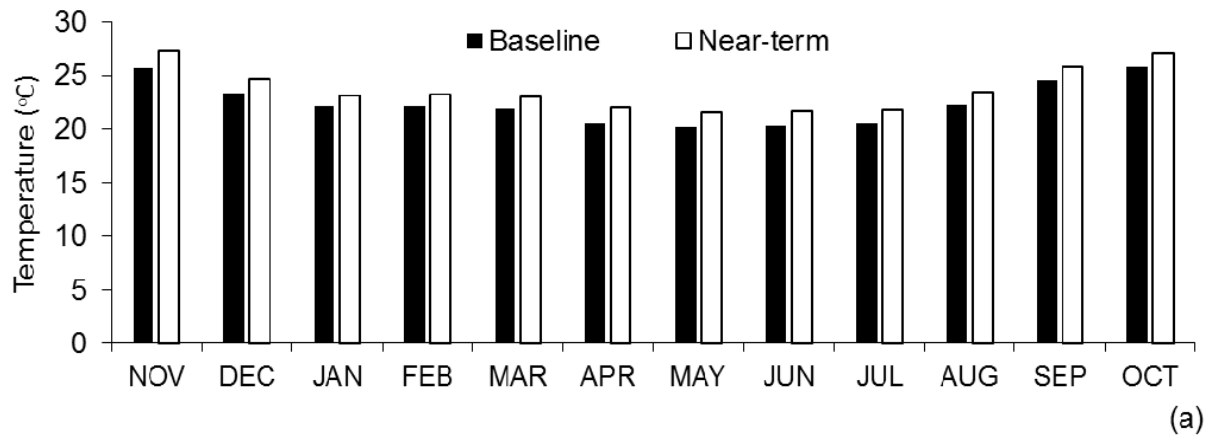


Figure 46: Average monthly maximum (a) and minimum (b) temperature of Ndembera watershed for baseline and near-term periods

4.3.5 Land use/cover change and its impact on the catchment water balance

The largest future land use/cover change between 2013 and 2020 were observed in the mixed forestlands (Fig. 47). The mixed forestland decreased by 12%. The areas under agricultural land were projected to increase by 10%, while evergreen forests increased by 7%. The shrub lands (Range-Brush) and grasslands (Range-Grasses) showed a decrease of 6% and 1%, respectively. Very small changes were observed for urban land and wetlands.

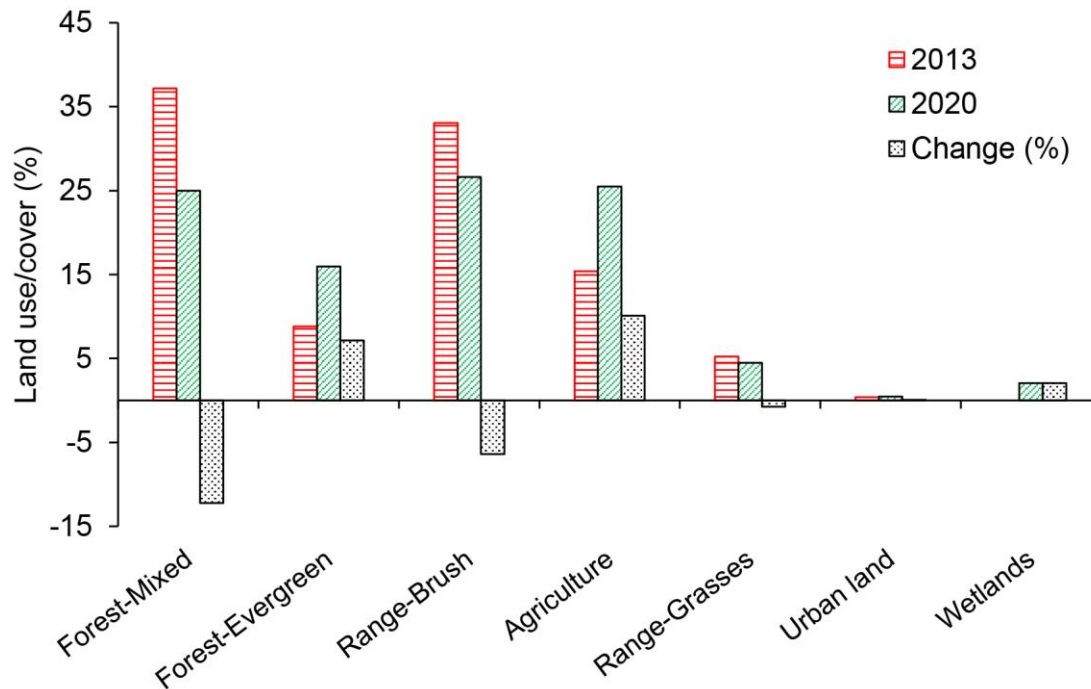


Figure 47: Land use/cover of the baseline (2013), future (2020) period and their changes

The observed land use/cover changes from 2013 to 2020 scenario affected the water balance of the watershed in a number of ways. These include a decrease of the total water yield and the lateral flow components by 32 mm/year (~13%) and 34 mm/year (~49%) (Fig. 48). On the contrary, the evapotranspiration and surface runoff increased by 30mm/year (~8%) and 5mm/year (16%), respectively. The amount of water loss from the channels during downstream flow (transmission losses) increased by 20 mm/year (88%). Some minor changes were noted for the rest of the components such as total aquifer recharge, shallow and deep groundwater flow and water percolating out of the soil.

Water balance ratios, the Streamflow/Precipitation and Baseflow/Total Flow indicated negative changes of -0.05 and -0.14, respectively (Table 20). On one hand, the baseflow contribution in the watershed total flow under 2013 and 2020 land use/cover scenarios were 0.78 and 0.64, respectively. On the other hand, the surface runoff contributed only 0.22 to 0.36, respectively. The ET/precipitation and Surface Runoff/Total flow ratios showed positive changes of 0.04 and 0.14, respectively. Furthermore, land use changes had no effect on the amount of precipitation that was partitioned into percolation and deep recharge.

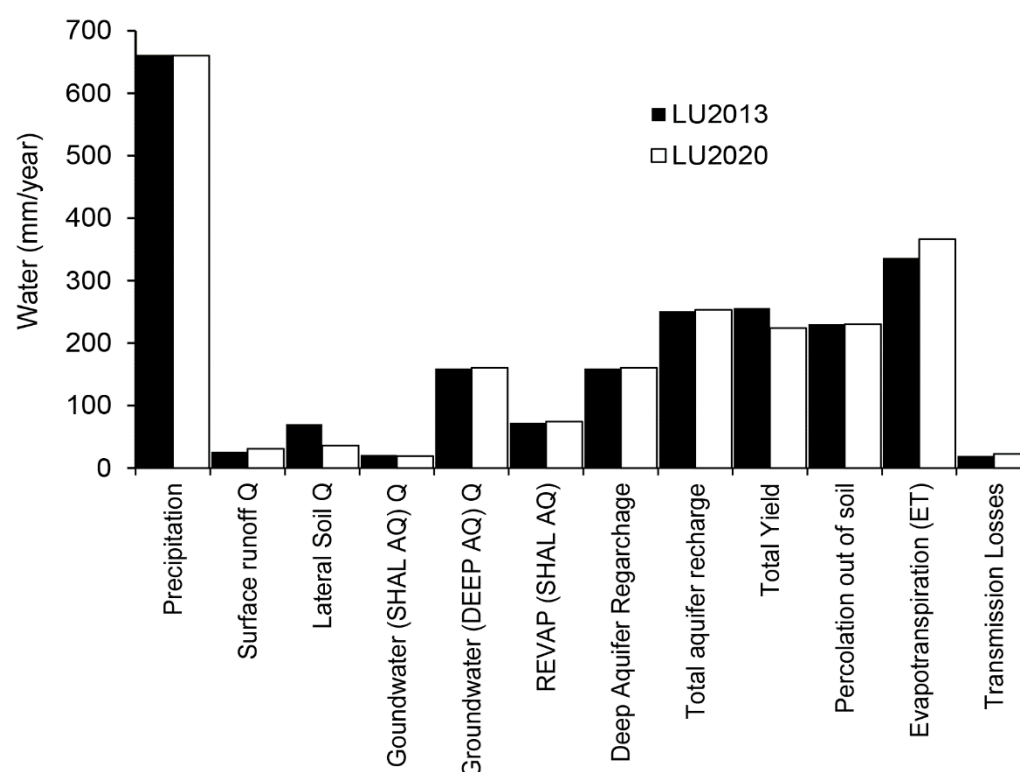


Figure 48: Water balance of Ndembera watershed under 2013 and 2020 land use/cover scenarios

Table 20: Changes in the water balance ratios under 2013 and 2020 land use/cover scenarios

Water Balance Ratios	LU2013	LU2020	Change
Streamflow/Precipitation	0.18	0.13	-0.05
Baseflow/Total Flow	0.78	0.64	-0.14
Surface Runoff/Total Flow	0.22	0.36	0.14
Percolation/Precipitation	0.38	0.38	0
Deep Recharge/Precipitation	0.24	0.24	0
ET/Precipitation	0.51	0.55	0.04

A comparison of the average monthly river discharge at 1ka33 for the baseline and future land use/cover scenarios showed small differences, both in the mean discharge values and the timing of ascent and recession of the hydrograph (Fig. 49). During the ascent of the hydrographs in December and January, the simulated mean monthly discharge under the 2020 land use/cover was above the baseline discharge, that is, 5 m³/s and 14 m³/s compared with 4.5 and 13 m³/s, respectively. On the contrary, during the recession of the hydrograph, from March-April (wet season) through June and October (dry season), the simulated discharge under the 2020 land use/cover was lower than the baseline discharge. In addition, there was a horizontal shift of the discharge hydrograph to the left, showing some early ascending and recession of the hydrograph in the wet months (Fig. 49).

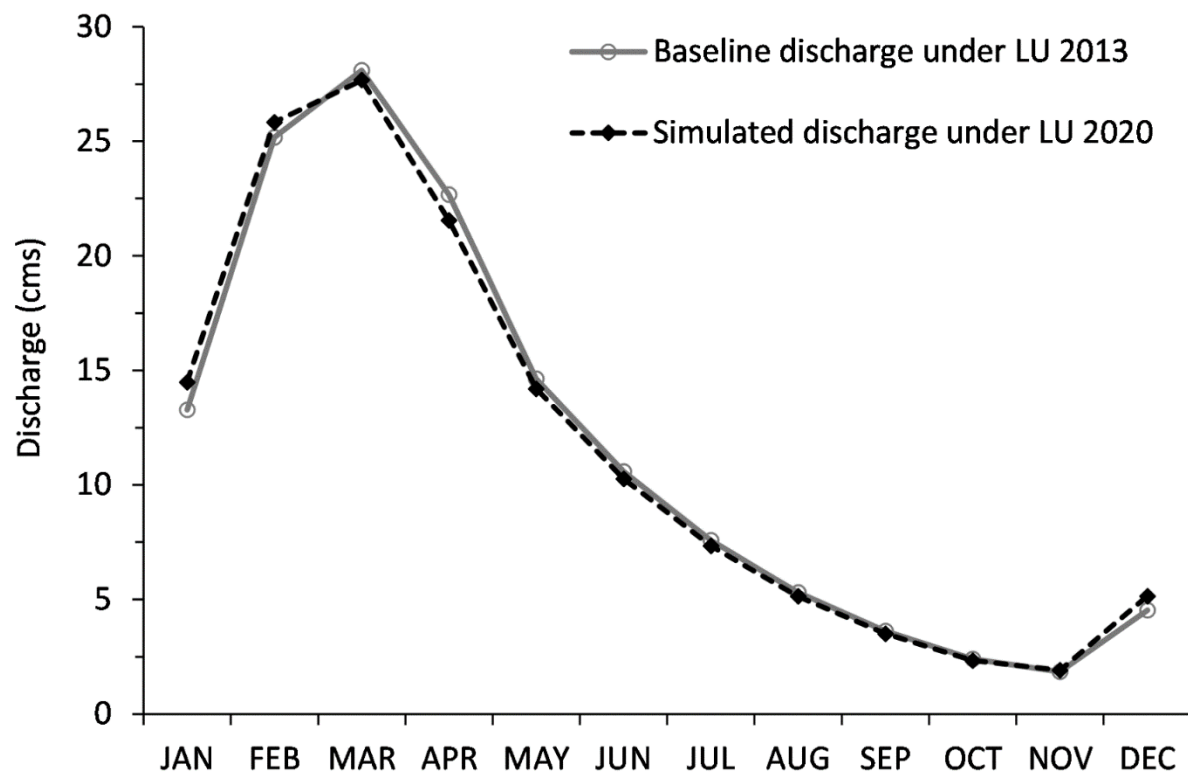


Figure 49: Ndembera River discharge at 1ka33 under the 2013 and 2020 land use/cover scenarios

4.3.6 Impact of future climate change on the catchment water balance

Near-term climate change affected water balance components by decreasing the lateral water flow from 70 mm/year to 35 mm/year (~100% change) and the total water yield from 260 mm/year to 240 mm/year, a decrease of ~8% (Fig. 50). The evapotranspiration increased

from 336 mm/year in the baseline to 453 mm/year (about 35% change). Compared with the baseline climate scenario, the surface runoff, total losses of water in channels during downstream flow and the Revap from shallow aquifer showed a relatively small decrease under the future climate change scenario. The shallow aquifer flow, deep aquifer recharge, groundwater recharge and percolation increased by a relatively small amount under the future climate scenario.

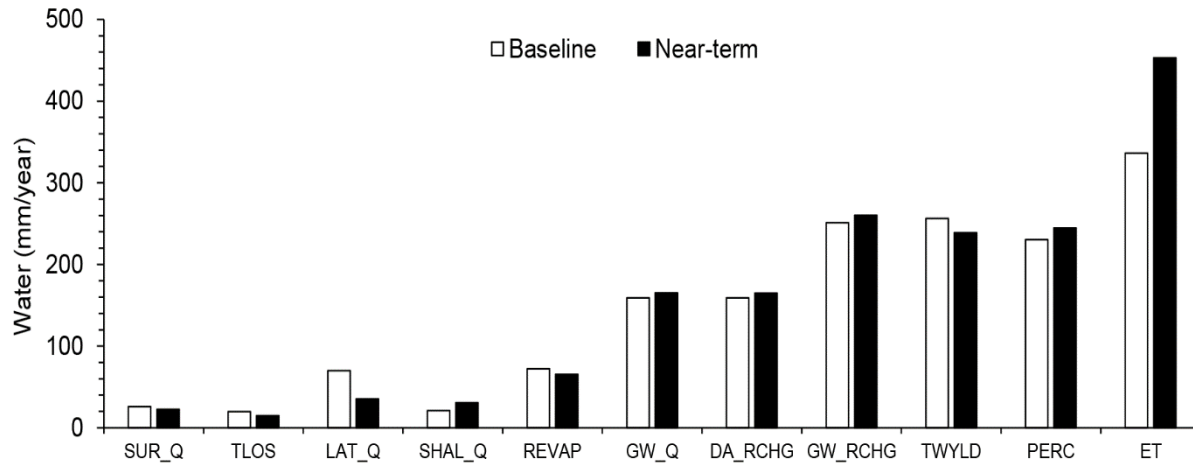


Figure 50: Near-term water balance simulated under the GCMs ensemble mean climate data compared to the baseline water balance

The near-term climate change scenario will increase the mean monthly river discharge for the near-term period relative to the baseline period (Fig. 51). Large differences between the baseline and future period flows were noted during the wet season, especially in the months of January-March. The February river discharge will increase from 25 m³/s in the baseline period to 30 m³/s in the future period (~21% increase). Similarly, in the month of March, the discharge will increase from 28 m³/s to 32 m³/s (~15% change).

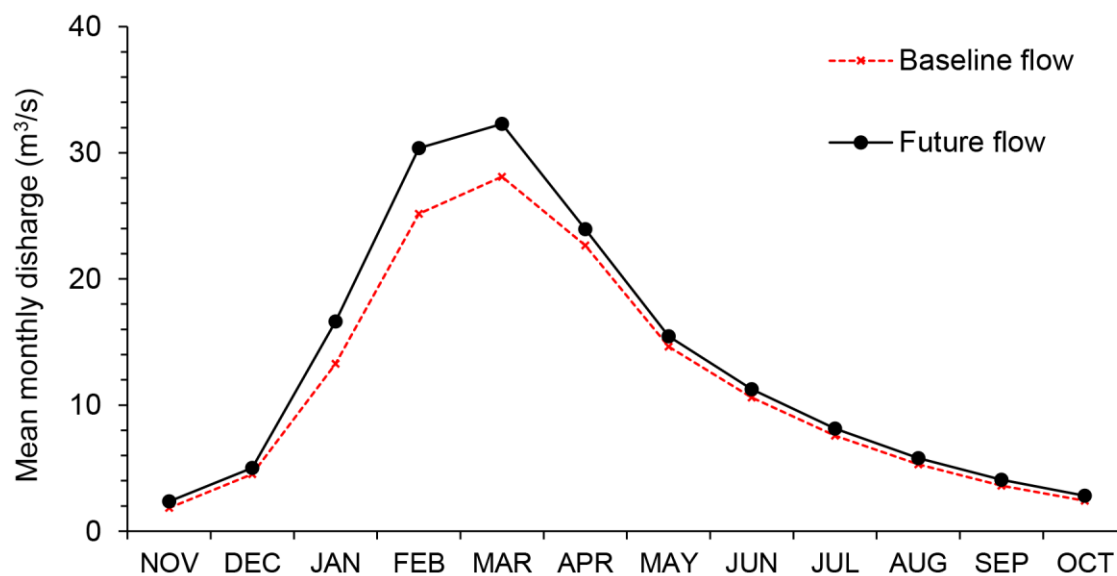


Figure 51: Mean monthly river discharge of Ndembera River at 1ka33 under the near-term climate scenario compared to the baseline

4.3.7 Impacts of management practices on water balance and river discharge

The simulation of water balance of the watershed under the four land and water management practices increased the amount of water in almost all water balance components (Fig. 52). The amount of evapotranspiration of water under filter strips decreased by almost 26 mm/year (~6%). Furthermore, filter strips decreased the surface runoff by 12 mm/year (~54%) while the deep ripper tillage decreased the transmission losses in streams by 10 mm/year (~66%). Unexpectedly, the grassed waterways and terrace and contouring management practices increased the surface runoff by equal intensity of 31% (~21-28 mm/year). In general, the filter strips showed relatively greater changes in the annual water balance in most of the components compared with other land and water management practices. Such changes included increase in the surface runoff from 21-83 mm/year, total water yield from 234-315 mm/year and the percolation from 234-261 mm/year. The deep aquifer recharge and total groundwater recharge an increased by 43 mm/year and 68 mm/year, respectively.

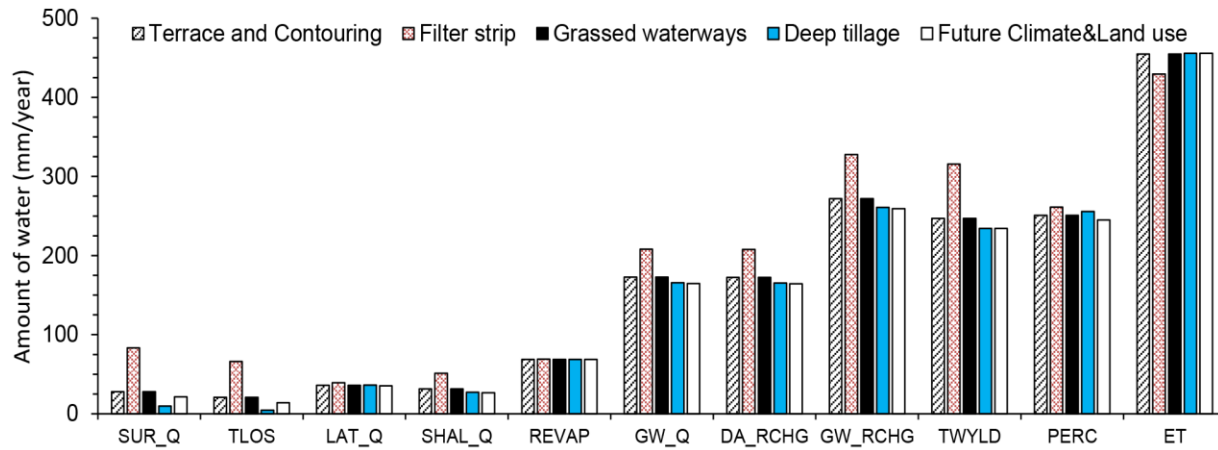


Figure 52: Water balance under specific land and water management scenarios compared to the reference water balance scenario derived from near-term climate

The river discharge increased for almost all management practices compared with the discharge under the near-term climate and 2020-land use discharge scenario except for the deep ripper tillage (Fig. 53). The simulated flow under the filter strip practices scenario showed higher discharge than other management scenarios throughout the year. The river discharge under the filter strips were as higher as 42 m³/s in February and March compared with 26 m³/s and 30 m³/s of the reference discharge (discharge under the effect of near-term climate change and 2020 land use/cover) during the same months. These changes represent a change of about 62% and 40%, respectively. The hydrographs of the terracing and contouring as well as grassed waterways were slightly lower than the one under filter strips throughout the year but higher than the reference discharge during the wet season (January-April).

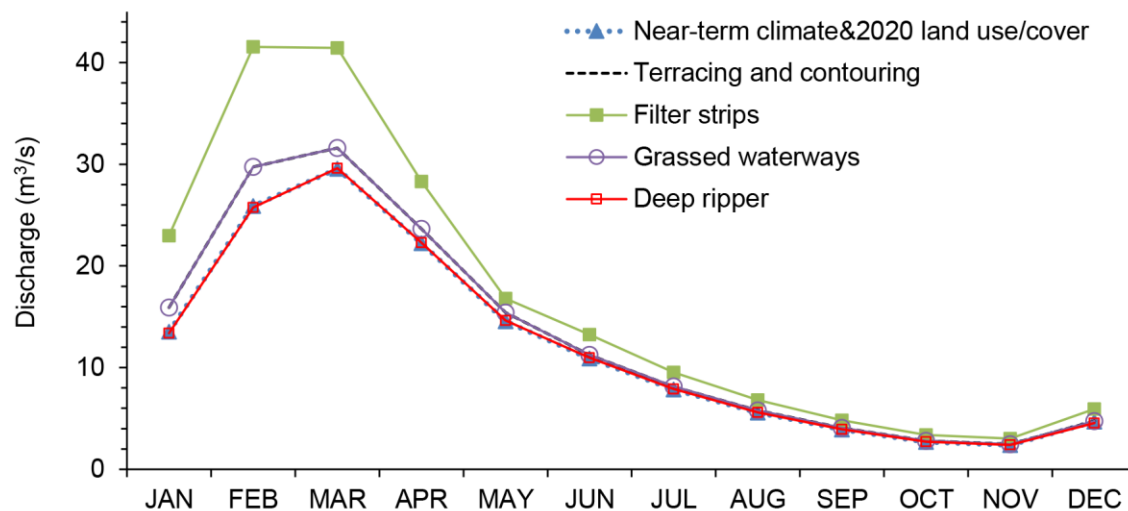


Figure 53: Hydrographs of Ndembera River at 1ka33 under different land and water management practices compared the reference hydrograph

4.4 Discussion

4.4.1 Model parameterization and sensitivity analysis

The sensitivity analysis from other watersheds in the East African region had, among the top six sensitive parameters, few parameters similar to the one found in the Ndembera watershed. For example, in Murchison Bay Catchment, Uganda, the CN_2, GW_DELAY and GW_REVAP were among the top six sensitive parameters to river discharge (Anaba *et al.*, 2017). The CN_2 and SOL_AWC were also among the most sensitive parameters reported in the Simiyu River Catchment in Tanzania (Mulungu and Munishi, 2007).

The parameters presented in Table 15 and their sensitivity information in Fig. 39 are significant to the body of scientific knowledge in two ways. Firstly, allow a more stringent evaluation of the reality of the parameters used in the model parameterization and calibration as well as the models itself as suggested by Kilonzo *et al.* (2012). Secondly, the results serve as a starting point of SWAT model parameterization in the subsequent studies within or in the nearby watershed that may need SWAT as a tool for hydrological processes related analysis. However, the parameter values may need some minor customizations because the catchments differ in their physical characteristics (Schmalz and Fohrer, 2009).

4.4.2 Adequacy of the SWAT model and GCMs-derived data for hydrological processes simulation

The NSE values in Table 18 are far greater than the acceptable values; $NSE > 0.5$ (Abraham *et al.*, 2007; Moriasi *et al.*, 2007). The PBIAS values -4.6 and 3.8 are within $PBIAS < |25\%|$, can be said to describe a satisfactory model performance for monthly data of the stream flow (Moriasi *et al.*, 2007; Dourte, 2011). Small PBIAS values in this study indicate a good mass balance in terms of volume between the observed and simulated discharge (Maharjan *et al.*, 2014). The satisfactory model calibration and validation results in terms of NSE, R^2 and PBIAS in Table 18 as well as a good match of the observed and simulated flows in Fig. 40a are interpreted as the outcomes of good model inputs and parameterization. The distributed rainfall information increases the simulation accuracy and predictive capacity of the model (Dwarakish and Ganasri, 2015).

Rainfall is an important data input for hydrological models (Strauch *et al.*, 2012). However, this data is not always available at some stations as was the case for the Ndembera Auto met. Similar challenges have also been reported in other countries including South Africa (Kapangaziwiri *et al.*, 2012) and Chile (Stehr *et al.*, 2008). The reasons for a situation include i) many drainage basins in the world are ungauged or poorly gauged and ii) the declining of the existing measurement networks (Sivapalan *et al.*, 2003). For this reason, therefore, it was necessary to merge the gauged rainfall data from Iringa Maji station with the CFSR satellite data sets that, in turn, generated the simulated river discharge that well matched with the observed data as observed in Table 18 and Fig. 40a.

The p -factor and r -factor results in Table 18 showed poor performance compared with other model performance evaluation statistic during the validation period. This is because only 48% of the observations were bracketed by the 95% prediction uncertainty envelope. If the measured data is of a high quality, then the p -factor should be >0.8 and the r -factor <1 (Abbaspour, 2007). Nevertheless, the p -factor value of 0.48 is close to 0.5, which is also sufficient under less stringent model quality requirements (Schuol *et al.*, 2008). One of the explanations for small p -factor and r -factor values could be the use of NSE as the objective function during calibration in the SWAT CUP-SUFI2, while the p -factor and r -factor were used as the uncertainty analysis tools. It is contended that, if one has the NSE as the objective function, by narrowing the parameter ranges, there is a possibility of getting a better NSE in

the subsequent iterations, but the p -factor and r -factor will decrease because of the narrower parameter range (Abbaspour, 2015).

During SWAT model calibration using SWAT-CUP SUFI2, the target was to bracket most of the measured data within the 95PPU, keeping a p -factor close to 1, while having the narrowest 95PPU band, and r -factor close to zero. Given the large uncertainty in this study (Fig. 40a and Table 18) depicted by the wider 95PPU band and r -factor of 0.61 and 0.65, it can be argued that it is a result of the quality of data input and model structure as it was also contended by Faramarzi *et al.* (2013) who studied the impacts of climate change on freshwater availability in Africa. It is acknowledged by Abbaspour (2015) that watershed models suffer from large model uncertainty. In addition, distributed hydrological model, SWAT is subject to large uncertainties (Pervez and Henebry, 2015). For the case of Ndembera SWAT model, the calibration-performance uncertainty in Fig. 40a and Table 18 could most probably be a result of data input uncertainty caused by errors in rainfall data from Iringa Maji weather station which was used in bias correction of the CFSR weather data from SWAT model. According to Abbaspour (2015), hydrological model outputs are very sensitive to input data, especially rainfall. Furthermore, large uncertainty of Ndembera watershed SWAT model could be the lack of understanding of the processes occurring in the watershed but not included in the model. One of the processes could be the illegal water abstraction from the river by small-scale farmers. There is an evidence of unauthorized withdrawal of river water for irrigated onions and rice in many villages along Ndembera River.

A good match between the GCMs-derived and the observed climate data (Fig. 41 and 42), may be associated with the strength of the quadrant method for CMIP5-GCMs sub-selection which was also previously used by Subash *et al.* (2016). Indeed, this observation is evidenced by high correlation values, small mean error values and closely related distribution statistical parameters (Table 19). These good validation results could also be attributed to ready-made functions used for the CMIP5-GCMs statistical downscaling and climate projection (Hudson and Ruane, 2013). Underestimated GCM climate in Fig. 42a&b could be partly attributed to the poor accuracy of the observed temperature data.

4.4.3 The trend of climate change in the Ndembera watershed

The increasing trend of the warmer conditions (1.1°C) in the near future (Fig. 44b), is mainly attributed to the increased CO₂ concentration and other greenhouse gases in the atmosphere at a global level (Edenhofer *et al.*, 2011). The trend and magnitude of temperature change in the near future period observed in this study does not differ much from 1.3°C by 2030 observed in a previous study in Tanzania (Laderach and Eitzinger, 2012). The same study reported an increasing trend of the annual precipitation as observed in the current study. In addition, the recent climate change projections study by Serdeczny *et al.* (2016) has also reported a warming trend in sub-Saharan Africa and increased precipitation in East Africa.

4.4.4 The impact of land use/cover change on water balance and river discharge

The decrease in the total water yield and lateral water flow and the increase in evapotranspiration and surface runoff depicted in Fig. 48 could be explained by the observed 2013-2020 land use/cover changes (Fig. 47). For example, the increase in evapotranspiration by 30 mm/year in Fig. 48 could be attributed to the 10% increase in agricultural land (Fig. 47), mainly the irrigated onion and rice farms. It is worth noting that the irrigated rice in small river watersheds in Usangu catchment has higher water demand than most crops because of the pre-saturation of the soil profile and the need for a standing water layer (Lankford and Franks, 2000). The large surface standing water in agricultural fields creates high possibility of water loss through evaporation. Another argument accounting for the increased evapotranspiration is the increase in evergreen forest (7%, Fig. 47) mainly the eucalyptus and pine commercial trees in Mufindi District. This implies the increase of more plant biomass and high leaf area index due to increased canopy. Usually, the canopy stores more water when the precipitation is intercepted and, therefore, making more amount of water available for evaporation (Wang and Kalin, 2011). The increase in evaporation from canopy and irrigated farms can also explain for the observed decrease in total water yield (Fig. 48).

The increase of surface runoff/total flow ratio (Table 20) is translated as the result of the increased agricultural area, urban land and a decrease of tree and grass cover in forests and rangelands (Fig. 47). The removal of forest trees and grass cover tends to increase storm runoff and decrease infiltration to groundwater and baseflow of streams (Kiersch, 2006). The

removal of forests reduces the infiltration opportunities that, in turn increases the amounts of water leaving the area as storm runoff and reduces the gain in baseflow. This usually diminishes the dry season flow (Kashaigili, 2008). According to Dagar *et al.* (2016), the use of machinery for various tillage practices causes the compaction of the soils. This scenario may account for the decrease in infiltration to groundwater, increased surface runoff and decline in baseflow observed in the current study. The increased surface runoff leads to an increased amount of water flowing to the streams in wet season and it can ultimately be lost through evaporation (Neitsch, 2009).

The decrease in the baseflow component from 0.78 to 0.64 under the 2013 and 2020 land use/cover scenarios in Table 20 complements the findings of continuous declining trend of baseflow across the Usangu catchment in the period between 1960 and 2009 (Shu and Villholth, 2012). The authors reported deforestation, irrigation and groundwater abstraction as the main factors causing the baseflow decline. Land use/cover change has been associated with the declining the baseflow in other studies conducted within the Usangu catchment (Kashaigili, 2008) and in other countries such as Botswana and South Africa (Palamuleni *et al.*, 2011).

The decrease in total water yield observed in Fig. 48 because of land use/cover change is mainly attributed to the decrease in forest cover. According to Palamuleni *et al.* (2011), the destructive land cover change may disrupt the hydrological cycle either through increasing or diminishing the water yield. In the current study, water yield decrease with decreasing forest cover contrary to the previous studies where water yield increased with forest reduction (DeFries and Eshleman, 2004; Feng *et al.*, 2012). The contradicting findings suggest that water yield is a function of factors other than the forest cover that in this case appear to have had greater influence on water yield. Such factors may include the increased evapotranspiration from increased agricultural areas (Fig. 47) or increased evapotranspiration due to the unaccounted recent decade-long temperature increase.

The horizontal shift of the river discharge pattern depicted in Fig. 49 is an indication of increased surface runoff due to the removal of vegetation cover because of expanding agricultural area and decrease of mixed forests (Fig. 47). The Great Ruaha river showed similar discharge pattern as a result of land use/cover change in the areas around the Ihefu

Wetland (Kashaigili, 2008). The observed low flows in the dry season under the 2020 land use/cover scenario (Fig. 49) signify reduced agricultural production especially irrigated rice at the Madibira and Mkunywa irrigation schemes. As reported earlier, the shortage of water downstream will have negative consequences on wildlife in the Ruaha National Park (Kashaigili *et al.*, 2006b).

4.4.5 The impact of near-term climate change on water balance and river discharge

The continued increase in evapotranspiration from 336 mm/year to 453 mm/year under the influence of the near-future climate change scenario (Fig. 50) is mainly attributed to the observed change of mean watershed temperature of 1.1°C (Fig. 44b) and the increase of both the mean monthly minimum and maximum temperatures (Fig. 46). The results imply that the evapotranspiration was underestimated when the impacts of land use/cover change were evaluated in isolation. The increased evapotranspiration is known to increase the water demand of plants and increase water stress which may reduce crop yields (Jensen, 1968). The possibility of a decrease in crop yields in the watershed due to the effects of global warming and the increase in temperature is supported by the findings from a previous study in Tanzania (Laderach and Eitzinger, 2012). In this study, it was found out that a change of temperature by +1.3°C would decrease areas suitable for coffee cultivation by 20-50% in 2050. Globally, 1°C increase in temperature in the developing countries will lower the growth in agricultural output by 2.66% (Dell *et al.*, 2012). One of the reasons for this is the increased evaporative loss (Beck and Bernauer, 2011). Nevertheless, increased evaporative loss may lead to increased yield of some crops. For example, a study by Jones *et al.* (2015) predicted that increased evapotranspiration by 6% coupled with increased CO₂ concentration fertilization will result in increased yield of irrigated sugarcane in South Africa during the 2070-2100 period. This implies that climate change brings with it potentials for crop production if appropriate adaptation measures are taken.

Despite the fact that the future climate scenario showed wetter and warmer conditions in the near-future than the baseline period (Fig. 45&46), the impact of precipitation seemed not to counter the effect of temperature on evapotranspiration. This resulted in the decrease of total water yield shown in Fig. 50. The observed increase in percolation, groundwater recharge, groundwater flow, shallow aquifer flow and reduced revap from the shallow aquifer in Fig. 50 is most probably the result of higher precipitation amounts in the future compared to the

baseline. The major reason being that the precipitation is a major component of water balance (Beeson *et al.*, 2011). The change in the amount of precipitation has also some implications on other water balance components (Neitsch, 2009).

The increase in the future river discharge in the wettest months of January to April (Fig. 51) corresponds well with the increase of the near-term mean monthly precipitations in the same months (Fig. 45). These results are in line with the observation by Taniguchi (2012) and Wambura (2014) that the increase in streamflow depends on the amount of precipitation. The future climate simulation also showed increased discharge of rivers during high flow in Bangladesh (Kirby *et al.*, 2016) and the Sahelian regions (Amogu *et al.*, 2010; Descroix *et al.*, 2012). The increase in high flows in the Ndembera River observed in Fig. 51 may have resulted from the combined effect of future climate and the 2020 land use. This scenario has high and positive potential for boosting irrigated agriculture in the downstream. These irrigated crops could be the high-temperature tolerant type such as sugarcane (Jones *et al.*, 2015).

4.4.6 The impact of land and water management practices as mitigation strategies

The observed changes in water balance such as decreased evapotranspiration and increased percolation, ground water flow and recharge as well as total water yield (Fig. 52) are dependent on land and water management practices. Contours and terracing reduce the steep slope of the land and, therefore, reduce and delay the surface runoff and allows a long time for rainwater percolation (Dou *et al.*, 2009). Deep ripper tillage increases soil depth and enhances percolation and ultimately reduces overland surface flow (Lacey, 2008). Grassed waterways reduce runoff volumes due to their comparably high infiltration rates and the reduction in runoff velocity. The grassed waterways reduced runoff by 10% and 90%, respectively, in the two watersheds in Munich (Fiener and Auerswald, 2003). This is contrary to the unexpected increased surface runoff in the current study of about 31% under both grassed waterways and terrace and contouring (Fig. 52). Nevertheless, in this study, the surface runoff under filter strips was higher than in other management interventions (Fig. 52). This is due to the fact that filter strips do not affect the surface runoff in SWAT (Arnold *et al.*, 2013). Moreover, high increase in percolation, shallow aquifer and groundwater flow, groundwater recharge and ultimately total water yield under the filter strips compared to

other management interventions is attributed to this increased infiltration rate (Arnold *et al.*, 2013).

The increase in streamflow under most of the management interventions observed in Fig. 53 is linked to the increased groundwater recharge due to the decrease of evapotranspiration as shown in Fig. 52. The reduced evapotranspiration and increased streamflow brought about by management practices contributes greatly to reducing the dependency on river for irrigation and reduce water competition between users (Lankford and Franks, 2000). In addition, these management practices will potentially mitigate the stress caused by the decline in available water resource due to climate change (Carpenter *et al.*, 1992).

4.5 Conclusion

The Ndembera SWAT model has been used to assess the impact of future climate and land use/cover changes on water balance and streamflow in the Ndembera River watershed. Further, the study evaluated the effectiveness of four land and water management practices as a way to mitigate impact of climate and land use/cover changes on water resource. The flexibility of SWAT to incorporate the future climate data from Global Circulation Models, predicted land use/cover from Markov Chain and Cellular Automata models paved a way to look into the future hydrological conditions of the Ndembera watershed.

Land use/cover changes such as the increase in the areas under agricultural lands, increase in evergreen forests and decrease in mixed forests from 2013 to 2020 are the major land use/cover changes responsible for water balance changes compared with other land uses. Water balance changes of great concern are the increases in evapotranspiration and surface runoff, and decreased water yield. Changes in these components decreased the baseflow and streamflow which ultimately decreased the availability of water within the watershed.

The superimposition of the near-future climate scenario on the impacts of the 2020 land use/cover changes, exacerbated the adverse hydrological impacts such as the increase in evapotranspiration and decrease in water yield. The decrease of forest lands, expansion of agriculture and urban lands in combination with the increase of the watershed's mean temperature by 1.1°C in the near-future period will lead to more water losses through evapotranspiration and overland surface runoff. Furthermore, the future warmer climate, in

turn, will make the watershed unsuitable for producing high temperature sensitive crops. Nevertheless, planting of high temperature tolerant crops such as sugarcane in the watershed could be one of the adaptation strategies. The success of growing crops that are tolerant to elevated temperatures will be realized by adopting land and water management practices which reduce loss and make more water available for crops.

Land and water management practices evaluated in this study have proved to be effective mitigation and adaptation measures for the observed adverse hydrological impacts of future climate and land use/cover changes. Among the four management practices which were evaluated, three of them namely filter strips, terracing and contouring and grassed waterways were the most effective. These practices had great effect in increasing groundwater recharge, groundwater flow, percolation and total water yield. Notably, filter strips were the most effective measures in reducing the evapotranspiration.

Ndembera watershed experience the loss of tree cover especially in the mixed forest areas. This reduces the potentials of the watershed to perform carbon dioxide gas sequestration function as well as loss of water through increased evapotranspiration and surface runoff. The replacement of trees should be encouraged, especially those ones which are adapted to the soil and climate of the planting area. In addition, the trees should be those with the moderate to aggressive development to occupy the site quickly. These trees should be able help in improving water retention capacity in the catchment as well as providing the multi-benefits. Such trees could include fruit trees or fodder for animals. These multi-benefit trees could also be planted as filter strip trees and on the edges of contours and terraces in the farms.

CHAPTER FIVE

5.1 General discussion

Water from high altitudes of the Usangu catchment, mainly springs, had low concentration of dissolved substances, expressed as TDS, suggesting short time of water-rock interaction (Hiscock, 2009; Kazemi *et al.*, 2012). This concentration increased along the elevation gradient from highlands to the lowlands (CHAPTER 1). Similar to TDS, the water sources found in high lands (mainly springs) had more depleted $\delta^{18}\text{O}$ values compared to wells in the low altitudes as previously reported in Ethiopia (Ayenew *et al.*, 2008). In addition, water in wells had high SiO_2 concentrations that had positive correlation with $\delta^{18}\text{O}$ values at 95% confidence level ($p=0.05$). Similar findings of progressive mineral dissolution in groundwater from high to low elevations have been reported elsewhere (Li *et al.*, 2014). Despite this highland to lowland increasing trend in the concentration of dissolved substances in water sources, there was no significant differences of dissolved substances in springs and rivers at 95% confidence level. This suggests that compared to groundwater (wells), the springs are the main contributors of water in rivers in the study area.

The close interconnection between springs and rivers (CHAPTER 1) can also signify the interdependence of rivers on springs and is likely to be negatively impacted by decrease of forest cover in the future as predicted by Markov-Cellular Automata models (CHAPTER 3). When the forest cover in the highlands (main groundwater recharge areas) decreases, it will reduce the rainwater infiltration into the soil and ultimately reduce annual groundwater recharge (CHAPTER 4). The reduction in groundwater recharge will, in turn, reduce the spring discharge and hence reduce river flows (Malley *et al.*, 2007; Rajabu, 2007; Mwanukuzi, 2011).

Despite minor seasonal variations, the stable isotopes composition of water (^{18}O and D) did not differ significantly in all water sources in Usangu catchment, indicating a recent recharge of aquifers. In addition, there was a downward (high to low elevations) enrichment of $\delta^{18}\text{O}$ in water in springs, wells and rivers caused by factors such as evaporative enrichment of surface water (Mckenzie *et al.*, 2010; Ghiglieri *et al.*, 2012) and isotopic exchange of ^{16}O of groundwater with ^{18}O of weathering silicates, evidenced by the positive correlation of $\delta^{18}\text{O}$ and SiO_2 concentrations in groundwater from wells (Clark and Fritz, 1997; Geyh *et al.*,

2008). Both lack of significant differences in the stable isotopes composition in water sources, and the slight altitudinal and seasonal differences, as well as a strong and positive $\delta^{18}\text{O}$ - SiO_2 linear relationship in wells in this study are important in tracing the source of recharge, interconnections between water sources and processes taking place in the groundwater.

The decreasing forest cover and increasing agricultural land trends in Usangu catchment reported by Kashaigili *et al.* (2006a) is still going on and is predicted to continue in the future (CHAPTER 3). This study shows that land use/cover types are very dynamic in the watershed, and the probability of most of the land use/cover categories, except grassland, to remain stable in the future is low (Table 12, CHAPTER 3). The land use/cover changes, in turn, are shown to impact moisture balance in the catchment in a negative way (CHAPTER 4). The impacts include the increase in the loss of water by evapotranspiration, increased surface runoff and the decrease in rainwater infiltration into the soil that, in turn, decrease groundwater recharge and streamflow discharge. Similar impacts of land use/cover changes have been observed in other catchments in Tanzania (Mulungu and Kashaigili, 2012; Natkhin *et al.*, 2015), Ethiopia (Shawul *et al.*, 2013) and China (Yin *et al.*, 2017).

These undesired changes in moisture balance emanating from the land use/cover changes are shown to be aggravated by the near term warmer climate, where temperature is expected to increase by 1.1°C from 2010 to 2039 (CHAPTER 4). The shortage of water due to the intensification of the impacts of land use/cover change by climate changes in Tanzania have also been reported in Ngerengere River watershed in Tanzania by Natkhin *et al.* (2015). In Usangu catchment, the decline in Ndembera river discharge during the dry season due to decreased groundwater recharge and increased evapotranspiration is anticipated to cause water stress downstream for agricultural activities such as irrigated rice at Madibira irrigation scheme. Further, it will result into low flows in Ruaha River across Ruaha National Park that affect wildlife and hydroelectric generation in the Mtera Dam. The economic and ecological impacts of low flows in Ruaha River due to hydrological changes in the upstream have also been discussed by Lankford *et al.* (2009), Malley (2011) and Kadigi *et al.* (2008).

In general the changes in land use/cover in Ndembera watershed have both direct and indirect impacts on food production and ultimately food security as reported in other parts of the

world (del Mar López *et al.*, 2001; Jiang *et al.*, 2013). For example, urban land is shown to grow by about 8.2% from 2013-2020 (Table 13, CHAPTER 3). About 8.5% of this growth is due to converting agricultural land to urban land. This suggests increased pressure on food security if new technologies of producing more food on the same land are not adopted. Indirectly, the increase of surface runoff, evapotranspiration and reduced infiltration as well as the decrease in river discharge in dry seasons due to changes in land use/cover such as decrease of grassland (19.6%), forestland (20.6%) and shrubs (6.9%), will cause water shortage for food production.

Despite the intensification of undesirable watershed moisture balance impacts of land use/cover changes by the increase of 1.1°C in the near term period, there is a great possibility to reduce these impacts through the applications of land and water management practices (CHAPTER 4). The observed decrease in evapotranspiration and increased infiltration, groundwater recharge (Fig. 51, CHAPTER 4), as well as Ndembera river discharge during the wet and dry season (Fig. 52, CHAPTER 4) are attributed to the modification of watershed terrain morphology such as slope (Dou *et al.*, 2009) and soil permeability properties (Lacey, 2008).

The application of land and water management practices create possibilities to adapt to climate change impacts on moisture balance and increase the availability of water for agricultural production within and the downstream of Ndembera watershed (CHAPTER 4). This will in turn, create possibility for food production for Tanzanian population. Nevertheless, the crops to be grown are supposed to be those which can tolerate the 1.1°C temperature increase in the near term period, of which sugarcane would be one (Jones *et al.*, 2015).

The understanding of the hydrological processes of the Usangu catchment such as water sources, flow pathways and interconnection between water sources using the stable isotopes of water ($\delta^{18}\text{O}$ and δD) and hydrochemistry in CHAPTER 2 prior to the subsequent analysis of impacts of land use/cover and climate change on water resources (CHAPTER 4) was paramount. Through this understanding, it was possible to describe the observed water balance and river discharge changes as predicted by the Soil and Water Assessment Tool (SWAT) in CHAPTER 4). According to Beven (2011) it is not sufficient to just predict the

discharge from the catchment area based on rainfall-runoff models without considering the information from tracers such as stable isotope and dissolved ions. The tracers help to improve the understanding of the catchment processes. The rainfall-runoff models such as SWAT have limitations to describe the water sources and pathways in the subsurface, therefore in the current study, the use of stable isotopes of water and hydrochemistry enabled to have direct understanding of the water sources, flow and pathways.

The understanding of the catchment water sources and interconnections facilitated the selection of the potential land and water management practices which could be the mitigation measure for the observed changes on water resources due to changes of both land use/cover and climate changes. For instance, having identified the existence of the quick spring-rivers flow system in Usangu catchment shown by the hypothetical catchment diagram (Fig. 17, CHAPTER 2), it was possible to select the potential land and water management practices as the mitigation strategies for the dwindling water resources due to climate and land use changes. Only those management practices capable of slowing down the quick spring-rivers flow system by reducing the surface runoff, evapotranspiration and increasing the subsurface water storage were selected. The modification of the catchment landscape and soil physical properties which initially enabled a quick spring-rivers flow pathway by the selected land and management practices slowed the water both the overland and subsurface flows. These modifications delayed the release of water from the subsurface into the river and therefore helped to buffer the level of water in the river (discharge) during the dry season as observed in CHAPTER 4.

5.2 General conclusion

The origin and flow path of water as well as the hydrological interconnections among the water sources in Usangu catchment have been revealed through the statistical and graphical analysis of stable isotopes of water ($\delta^{18}\text{O}$ and δD), major dissolved ions (K^+ , Na^+ , Mg^{2+} , Ca^{2+} , Cl^- , CO_3^{2-} , SO_4^{2-}) and dissolved silica (SiO_2). The origin of waters in rivers, springs and wells in the study area have been found to be from the local and recent meteoric water; such that, the springs, mainly located in the high elevations (>1200-2000 m.a.s.l), are closely connected to rivers through a short flow path from recharge areas. The chemistry of water in wells located in the low elevations (1080-1170 m.a.s.l) differs significantly from spring and rivers by having high concentration of dissolved ions; suggesting a different flow path and

prolonged rock-water interaction. A more pronounced factor which brings the difference between springs, rivers and groundwater is ostensibly the prolonged rock-water interaction. Therefore, the combination of analysis techniques of the stable isotope compositions of water ($\delta^{18}\text{O}$ and δD) and major dissolved ions such as analysis of variance, cluster analysis, factor analysis and graphical methods (Piper, Schoeller and Gibbs) can provide a very useful information about the hydrological processes in a catchment where long term hydrological data are lacking.

The Markov Chain and Cellular Automata land use/cover predictive model of Usangu catchment has generated plausible and satisfactory simulation results for short-term forecasting of land use/cover change. The models showed that land use and covers of Usangu catchment are very dynamic; whereby, the future land use/cover changes (2020) show that the land area under urban, bare lands and agricultural lands will continue to increase while forestlands will decrease. Such land use/cover changes are of great concern as they have shown to affect moisture balance of the watershed through increased evapotranspiration and surface runoff, and decreased water yield. They, in turn, bring changes such decreased baseflow and streamflow. These changes decreased water availability within and downstream of the watershed for agricultural production and maintenance of Ruaha National Park ecosystem.

The negative impacts of future land use/cover changes will be worsened by hotter temperature conditions that the GCMs have predicted; namely, the increase of about 1.1°C during the near-term period (2010-2039). Such increase in temperature will lead to more water losses by evapotranspiration. Despite the fact that the future climate scenario showed wetter and warmer conditions in the near-future than the baseline period, the impact of precipitation is shown not to counter the effect of temperature on evapotranspiration. This, in turn, will make the watershed unsuitable for producing high temperature sensitive crops. In addition, since Ndembera River contributes about 15% of the Great Ruaha flow, the reduced river discharge will, in turn, intensify water shortage for wildlife in the Ruaha National Park during dry season, and reduce the capacity of dams such as Mtera to produce the hydroelectricity.

Although future land use/cover change will interact with warmer near-term climate and impact the moisture balance of Ndembera River watershed in a negative way, land and water management practices evaluated in this study showed to be effective interventions for such negative hydrological impacts. The filter strips, terracing, contouring and grassed waterways are the most effective interventions. This is largely due to increasing groundwater recharge, groundwater flow, percolation and total water yield. Nevertheless, the filter strips are the most effective measures recommended to reduce evapotranspiration.

There is a great potential of using the algorithms and procedures that are commonly used in the Agricultural Model Intercomparison and Improvement Project (AgMIP) to downscale the CMIP5-GCMs. They can also be used to select the subset of GCMs that are most representative of five possible weather conditions (hot/wet, hot/dry, cold/wet, cold/dry and mean) of certain location for generating GCMs climate data for hydrological modelling using SWAT. These algorithms and procedures generated plausible GCMs derived climate data that compared well the observed historical climate data. Nevertheless, in order to confirm the usability of the AgMIP algorithms and procedures to generate GCMs data for SWAT, there is a need to carry out several and similar studies in other watersheds. If such studies in other watersheds give results that validate the use of these AgMIP algorithms and procedures, then, there will be in place a universal, simple and quick method for downscaling and selection of GCM subsets to generate future climate data for SWAT. In this regard, watershed modellers will be able to repeat the same analysis with a standard procedure for comparison purposes.

5.3 Scientific contribution

Through the use of integrated analysis techniques on δD and $\delta^{18}O$ and water chemistry data, namely Principal Component Analysis, Hierarchical Cluster Analysis and ANOVA test, as well as graphical methods such as Piper, Gibbs, Schoeller and other ionic ration diagrams, the interconnections of surface and subsurface water, the possible origin and flow pathways of Usangu catchment has been revealed. The integrated techniques approach used in the current study to analyze the isotopes and hydrochemical data provided an extra dimension for determination of the relationship among the waters from different sources. Not only the results from one technique could be used to explain the results from other techniques, but also compensated for the weaknesses associated to one technique. For instance, the PCA enabled to reveal that the chemistry of waters could be defined mainly in terms weathering of

carbonate and silicate minerals (Factor 1) and stable isotopes composition (Factor 2). The weathering of carbonate and silicate minerals as the major sources of dissolved substances were confirmed by the $\text{Ca}^{2+}/\text{Mg}^{2+}$ ionic ratio. Also, the ANOVA and Tukey-HSD showed waters from rivers and springs do not differ significantly, but they differ from the water from wells. This was also confirmed by cluster analysis, however, the natural processes controlling the abundance of dissolved ions could not be explained, until the Gibbs diagram was used. Furthermore, although Piper diagram helped to display the hydrochemical facies of water sources, it does not accommodate the SiO_2 which was very important parameter occurring at high concentrations in water sources. The SiO_2 - $\delta^{18}\text{O}$ relationship has enabled to reveal the isotopic exchange fractionation in the ground water.

The study managed to define the possible flow path of water from high groundwater recharge areas (highlands) to the low elevation areas through the use of TDS-Elevation and SiO_2 - $\delta^{18}\text{O}$ relationships. The possible flow paths are suggested in Fig. 17. In addition, in the absence of boreholes log data, the possible chemical reactions and isotopic fractionation mechanisms taking place along the high to low elevation flow directions have been deduced though the use of ionic ratios, the SiO_2 - $\delta^{18}\text{O}$ relationships and distribution of $\delta^{18}\text{O}$ - δD values on the scatter plot along the LMWL.

The quantification of land use/cover changes and their implications on the water resources in Usangu catchment have been carried out by previous researchers such as Mwalukasa (2002), Kashaigili *et al.* (2006a), Kashaigili *et al.* (2006b), Canisius *et al.* (2011) and Lyimo (2017). They covered only a part of Usangu catchment, especially Usangu wetland, and none attempted to show the future land use/cover scenario of the whole Usangu catchment. Furthermore, the impacts of historical land use/cover changes were limited to river discharge and the wetlands hydrological changes. In this regard, the information of land use/cover changes of the whole catchment and its important river watersheds such as Kimani, Ndembera and Kyoga remained unknown. In addition, the impact of historical and future land use/cover changes on other hydrological/water balance components rather than streamflow, such as evapotranspiration, groundwater recharge, water yield and runoff have not been studied. Again, the way the future land use/cover will interact and impact the moisture balance of the watershed have not been analyzed in detail. In this study, the cellular automata and Markov models were used to generate the future (2020) land use/cover

scenario of the whole Usangu catchment, and simulate its impacts on the water balance components of the Ndembera catchment. The near-term (2010-2039) climatic variables were derived from statistically downscaled GCMs. This study revealed that future (2020) land use/cover change will interact with the future climate (increased temperature by 1.1°C) and exacerbate the negative impacts on moisture balance of the watershed such as decreased river discharge and groundwater recharge and increased overland surface runoff.

The suitability maps which were prepared using factors, constraints, membership functions and control points (Table 10) are original data created under the authors' knowledge of the watershed. The knowledge of the physical-demographic characteristics which influence land use/cover change and spatial distribution on the landscape enabled to make parameterization of factors during the MCE, the choice of the decision rule and range of values for control points. Such innovation generated a good simulated land use/cover 2013, which was validated and proved suitable for simulating the 2020 land use/cover. The knowledge (CHAPTER 3) and values (Table 10) can serve as easily customizable model for land use/cover studies in other watersheds in the East African region and elsewhere with minimum modifications of the control points in the standardization of factors using different fuzzy functions for criterion development.

This study on simulation of future land use and cover change is probably the first one for Usangu catchment as far as literature search showed. Therefore, the water resource managers and experts can use the calibrated and validated Markovian and Cellular Automata land use/cover change predictive model of Usangu catchment for simulating future water resources scenarios in the catchment. The 2020 land use/cover from the CA-Markov model is not only the input data for water balance models, but also an important tool for preparation of future ecological conservation plans. The operational CA-Markov land use/cover change predicative model of Usangu watershed prepared in this study will make some revolutions in the classical approaches of landscapes and water resources management. The classical conservation plans are reactive in nature (Connor, 2015), meaning that they are made based on a reaction on the causes of the present ecological problems. They fail to look into the future and put mitigation measures in place, a scenario that would enhance the risk of ecosystems damage. This study foresaw the possible changes in surface-subsurface moisture

due to the future climate and land use/cover changes, and evaluated possible land and water management interventions to reverse the impacts (CHAPTER 4).

The meteorological and river flow data in most of African countries are characterised by missing observations and sometimes not available at all (Ndomba *et al.*, 2005; Dile and Srinivasan, 2014). It was the same case for Usangu catchment. This study addressed the weather data scarcity challenge by incorporating the satellite weather data, known as the Climate Forecast and System Reanalysis (CFSR). The bias correction of CFSR using the observed precipitation data produced weather data with no gaps. This approach made it possible to have reliable precipitation data for simulating the hydrological processes in the watershed using SWAT. Therefore, this study gives an insight that it is possible to use the world weather data for SWAT (CFSR) for hydrological modelling in semi-arid watersheds.

The study provides a new insight on sensitive parameters to river flow in Ndembera River watershed. The study identified 19 influential parameters that can be used in the future for SWAT model calibration in the same area. The parameterization of SWAT model was based on the experts' knowledge of watershed's actual soil, land use/cover and terrain characteristics. This enabled to make an operational and useful model for simulating water balance in the watershed. Worthy mentioning, in addition to the 19 sensitive parameters (Table 15), the great efficiency of the Ndembera SWAT model to simulate river discharge is attributed to the ability of scheduling the management operations for crops in the model based on the crops growing calendar of the watershed (Table 14). To the best of the authors' knowledge, as of July 2017, there was no any other research in Usangu catchment or its small river watersheds that had published the SWAT calibration parameters as recommended by Griensven *et al.* (2012). Therefore, results of this study are expected to serve as a starting point for SWAT model parametrization for other studies in the Ndembera river watershed that will need SWAT as a tool for analysis and decision-making.

The future climate data from GCMs for the Ndembera SWAT model was generated using the algorithms and functions from the Agricultural Models Intercomparison and Improvement projects (Hudson and Ruane, 2013; Ruane *et al.*, 2015). These algorithms and functions were customized in the R Statistical software environment to enable the statistical downscaling and sub-selections of CMIP5-GCMs for the three satellite weather stations that fall within the

Ndembera watershed (Fig. 29). The study revealed that it was also possible to apply the same algorithms and functions to generate the historical and future GCMs climate variables for the Ndembera SWAT model, a rainfall-runoff model.

The simulation of water balance and river discharge impacts based on various land and water management practices have revealed the potential of such practices in reducing water stress in the watershed due to future climate and land use/cover changes. The effectiveness of the five management practices were compared and the three most effective ones in increasing water storage in the watershed were identified. Thus, these alternative land and water management practices can be used as one of the approaches for climate change impacts adaptation.

5.4 Recommendations

From this study, the following are recommended:

- i. Future studies which will require the use stable isotopes of water ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) should collect precipitation samples from the areas with high groundwater recharge potential. In addition, a continuous sampling of the precipitation for the whole rainfall period should be done to get a good mean isotopic signature in the whole rainfall season.
- ii. The age of water was not considered in this study. Future studies aiming to generate more information about the sources, flow paths and interconnection of water sources in Usangu watershed should include tritium isotope ($\delta^3\text{H}$) and carbon-14 (^{14}C) to determine the age of water from the springs, rivers and wells.
- iii. The subsurface water flow paths in Ndembera watershed were conceptualized in this study based on statistical and graphical analysis of water chemistry and isotopic composition. Aquifer depth, inclinations and other subsurface physical characteristics remain unclear. Further studies involving geophysical survey to map specific type and the exact depth of aquifers are recommended for better understanding of water resources in the watershed. This will enable to device some proper water resource use planning and protection. In addition, the study recommends for a study on hydraulic head mapping in the area to justify groundwater abstractions as the case of decrease in baseflow.
- iv. Climate change is a global and regional phenomenon. At global level, the reduction of the greenhouse gas emissions by afforestation, reforestation and the use of clean energy

such as solar power are encouraged as some of the means to address the climate change problem. In addition to these global approaches, the local administrations within the small watersheds should encourage the farmers to adopt land and water management practices at farm level as a climate change adaptation strategy.

- v. SWAT model was set for Ndembera River watershed only as a representative watershed in Usangu catchment. The SWAT calibration parameters showed good calibration and simulation results. Therefore, there is a need to test their transferability to some nearby river catchments to ascertain their use as a standard SWAT model for the whole Usangu watershed.
- vi. The Rufiji Basin Water Board (RBWB) in collaboration with local government authorities (LGAs) should put in place some deliberate efforts to increase forest cover in the highlands and on the steep slopes. These efforts will help to reduce surface runoff and increase the percolation of precipitation water that will ultimately increase groundwater recharge and hence the increase in the baseflow component.
- vii. Filter strips, grassed waterways as well contouring and terracing should be advocated or made as one of the land and water management policies in all small river watersheds in Usangu catchment so as to enhance resilience to the impacts of climate change.

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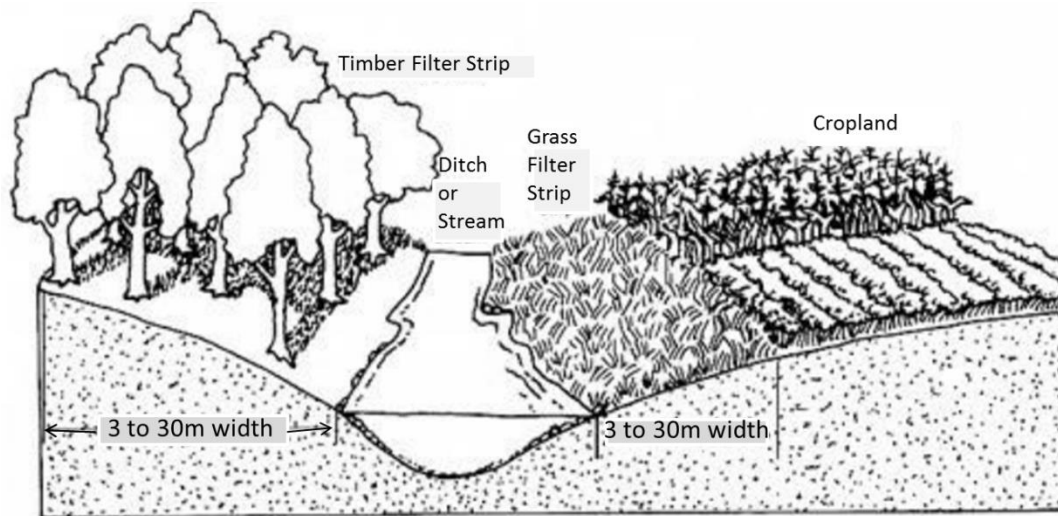
APPENDICES

Appendix 1: Names, Coordinates and Codes for each sampling site

Source	CODE	Site	Easting	Northings	Elevation(m)
Rivers	R1	Ruaha (Msembe)	709739	9146947	818
	R2	Ndembera	701497	9090784	1073
	R3	Kimani	628276	9022694	1078
	R4	Ruaha (Lunwa)	619042	9021028	1083
	R5	Kioga	659173	9040844	1083
	R6	Mbarali	650882	9030318	1101
	R7	Chimala	612507	9020466	1151
	R8	Mswiswi	585526	9029701	1152
	R9	Igurusi	595452	9023750	1196
	R10	Ipatagwa at Ilongo	575143	9025123	1252
Springs	S1	Mswiswi Spring	584551	9014550	1818
	S2	Ndembera Spring	776141	9094578	1913
	S3	Chimala Spring	605837	9010366	2016
	S4	Igurusi Spring	593245	9015306	1527
	S5	Ilolo Spring	594383	9025307	1179
Precipitation	P1	Chimala	606800	9011600	2005
	P2	Iringa/Ifunda	776141	9094578	1913
	P3	Igurusi	593797	9020482	1296
	P4	Mswiswi	585626	9029503	1169
	P5	Igawa	651000	9031000	1109
	P6	Rujewa	651454	9037008	1082
Groundwater	D1	Kabute well	702206	9091565	1078
	D2	Joseph well	651753	9038437	1079
	D3	Chimala Mission well	613563	9020231	1169

Appendix 2: Soils and Water Management Practices

i. Filter Strips



Source: Ohio State University Extension

Filter strips are vegetated areas that are situated between water bodies (i.e. streams and lakes) and cropland, forestland, or disturbed land. Filter strips are also known as vegetative filter or buffer strips. Strips slow runoff water leaving a field so that larger particles, including soil and organic material can settle out (Waidler *et al.*, 2011).

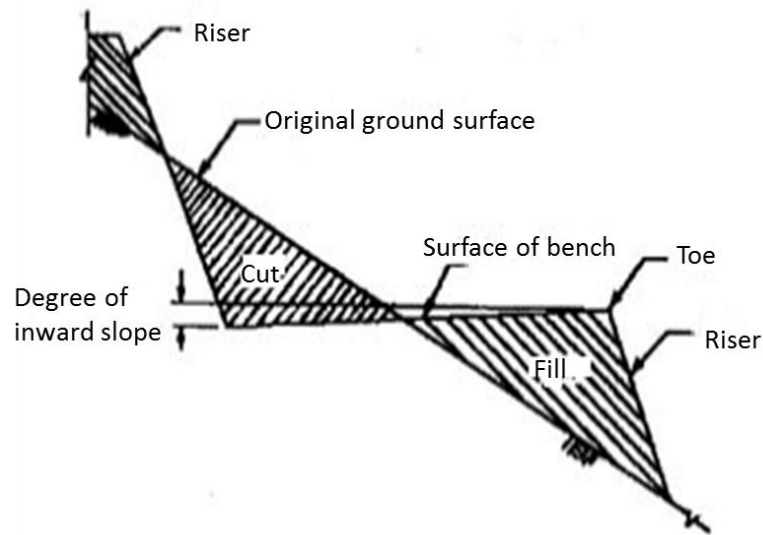
ii. Grassed waterways



Source: Waidler *et al.*, 2011

Grassed waterways are natural or constructed channels established for the transport of concentrated flow at safe velocities using adequate vegetation. The vegetative cover slows the water flow, minimizing channel surface erosion. The vegetation improves the soil aeration and water quality due to its nutrient removal through plant uptake and sorption by soil (Waidler *et al.*, 2011).

iii. Terracing



Source: Source: Waidler *et al.*, 2011

Terraces refer to an earth embankment, or a combination ridge and channel, constructed across the field slope. This practice applies where soil erosion caused by water and excessive slope length is a problem, excess runoff is a problem and there is a need to conserve water. Terracing requires that the soils and topography are such that terraces can be constructed and suitable outlet can be provided. In general, terraced fields are also farmed on the contour (Waidler *et al.*, 2011).

iv. Deep Ripper subsoiler



Source: <https://www.agric.wa.gov.au/sites/gateway/files/Deep%20ripping%20-%20deep%20ripper.JPG>

The deep ripper subsoiler helps to break the soils hardpan that allows more water infiltration, capture and storage in the soil (So and Ringrose-Voase, 2000).