MODELLING GROUNDWATER-SURFACE WATER INTERACTIONS AND RECHARGE DYNAMICS IN THE USANGU PLAINS, TANZANIA

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A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN IRRIGATION ENGINEERING AND MANAGEMENT OF SOKOINE UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.

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EXTENDED ABSTRACT

In Tanzania, irrigated and rainfed agriculture is a key sector of the national economy, and it accounts for more than 75% of the population's livelihoods. In the Usangu Plains located in the Southern Highlands of Tanzania, little is known about the groundwater recharge dynamics and its interactions with surface water bodies, despite the fact that the area is rich in research initiatives. Consequently, the irrigation schemes and other water user sectors are using groundwater and surface water without a clear understanding of the contribution of each of the two water resources.

This study modelled the groundwater-surface water interactions and recharge dynamics in the Usangu Plains. Specifically, the study evaluated the groundwater recharge dynamics in the Usangu Plains using the WetSpass model, analyzed water exchange processes between groundwater and surface water in the Usangu Plains and evaluated the future climate change influence on the groundwater recharge in the Usangu Plains. The GIS-based hydrological WetSpass model was used to evaluate the groundwater recharge dynamics and the future climate change influence on the groundwater recharge while the hydrograph separation techniques were used to analyze water exchange processes between groundwater and surface water. About 13.1% of the mean annual rainfall was found contributing to the groundwater storage. Approximately, due to the lack of groundwater withdrawal information during this study, 0% to 10% of the annual recharge were tentatively considered to be cautiously extracted for economic and domestic use. Except for Great Ruaha River at Msembe, other five rivers manifested a great dependence (more than 90%) on groundwater discharges. Nevertheless, the projected climate change and variations are expected to provoke the decrease of groundwater recharge quantity and distributions within the Usangu Plains. As a result,

the surface water volumes will decline as they are used to be sustained by the baseflow. Therefore, in addition to rainwater saving initiatives, effective policies to cope with and mitigate the climate change effects towards groundwater recharge dynamics will guarantee the water availability to meet the future economic, domestic use and crop water requirements.

DECLARATION

I, **Thomas Sahinkuye**, do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my own original work and that it has neither been submitted nor being concurrently submitted for a degree award in any other institution.

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LIST OF ABBREVIATIONS AND SYMBOLS

AET	Actual Evapotranspiration
a.m.s.l	Above mean sea level
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System
BFI	Baseflow Index
BFI_FI	Baseflow Index for Fixed Interval method
BFI_LM	Baseflow Index for Local Minimum method
BFI_SI	Baseflow Index for Sliding Interval method
CNRM-CERFACS	Centre National de Recherches Météorologiques-Centre Européen de Recherche et Formation Avancée en Calcul Scientifique
CORDEX	Coordinated Regional Climate Downscaling Experiment
CRU	Climatic Research Unit
CSV	Comma Separated Values
CV	Coefficient of Variation
DEM	Digital Elevation Model
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organization
GCMs	Global Climatic Models
GIS	Geographic Information System
GNR	Great North Road
GRR	Great Ruaha River
GW	Groundwater
IDW	Inverse Distance Weigh
IPCC	Inter- Governmental Panel for Climate Change

IUCN	International Union of Conservation Networks
LULC	Land Use Land Cover
MK	Mann - Kendall
NASA-POWER	National Aeronautics and Space Administration-Prediction of Worldwide Energy Resources
NetCDF	Network Common Data Format
RBWB	Rufiji Basin Water Board
RCA4	Rossby Center Regional Atmospheric
RCMs	Regional Climatic Models
RCP	Representative Concentration Pathway
SD	Standard Deviation
SMHI	Swedish Meteorological and Hydrological Institute
SMUWC	Sustainable Management of the Usangu Wetland and its Catchment
SR	Surface Runoff
SRTM	Shuttle Radar Topography Mission
SUA	Sokoine University of Agriculture
SWAT	Soil and Water Assessment Tool
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
URT	United Republic of Tanzania
USA	United States of America
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WB	World Bank
WCRP	World Climate Research Program
WetSpass	Water and Energy Transfer between Soil, Plants and Atmosphere

	under quasi-Steady State
WMO	World Meteorological Organization

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Information

Groundwater is one of the most important natural resources for economic development, environmental sustainability and remains a substantial part of the hydrologic cycle (Bhanja *et al.*, 2018). Groundwater can be recharged directly from precipitation, locally from depressions and rivulets, indirectly from rivers, irrigation losses (Vries and Simmers, 2002), urban recharge and intermediate recharge (Scanlon *et al.*, 2002). Recharge dynamics are affected by climate change and the influence is projected to increase due to future climate variability (Mohan *et al.*, 2018). The comprehension of the groundwater recharge dynamics is critical for reliable climate change adaptive measures and the quantification of the mechanisms of water exchanges between groundwater and surface water.

Groundwater and surface water are not isolated components of the hydrologic system, but instead interact in a variety of physiographic and climatic landscapes (Sophocleous, 2002). The interaction between surface water and groundwater takes place in the hydrologic cycle (Wohlgemuth, 2016). That connection determines the extent of water exchanged between the two domains and understanding the nature of this connection is fundamental when assessing groundwater management strategies (Cynthia, 2012). However, in Tanzania, there is inadequate data and information for major aquifers, hence the lack of groundwater resources management (Mahoo *et al.*, 2015).

1.2 Problem Statement and Justification

An understanding of the interaction process between groundwater and surface water in many regions has been proved necessary for the satisfactory operation and long-term planning of water resources schemes (Ruíz, 2015) and water sources management. Groundwater-surface water interactions remain poorly understood in many catchments throughout the world (Tanner and Hughes, 2015). Furthermore, little is known in Mbeya region about the groundwater evaluation and its interaction with surface water (Kashaigili, 2010). In the Usangu plains, there is a great lack of understanding regarding groundwater recharge dynamics, though it has been conclusively noted that recharge flux studies should be carried out frequently for the monitoring purposes (Rwebugisa, 2008). Limited knowledge concerning the effects of future climate change on groundwater resources is available (Benedict, 2019). In addition, limited information is available on the estimates of recharge flux for Usangu plains. Until recently, the available information of estimates for underground water recharge flux are that of the Makutupora groundwater basin which provides ranges between 1% to 2% of annual rainfall (Rwebugisa, 2008). Consequently, suitable information about future climate change influence on groundwater recharge dynamics in the Usangu Plains is scarcely documented.

Therefore, this study was designed to analyze the groundwater recharge dynamics and the interactions between groundwater and surface water to generate the understanding of the recharge dynamics and the groundwater-surface water interactions. Also, this study targeted the evaluation of future climate change effects towards groundwater recharge dynamics. The quantification of the groundwater recharge dynamics is very necessary for its efficient management (Huet *et al.*, 2016).

This may lead to the comprehension of when and where to establish groundwater abstraction wells and boreholes for irrigation, domestic use, industrialization, and the mechanisms for conjunctive use of groundwater and surface water in the Usangu Plains.

The knowledge of water exchanges between groundwater and surface in the Usangu plains is expected to enhance the sustainable management of the two water sources. Furthermore, the understanding of future climate variability influence on the available groundwater resources and recharge dynamics is necessary for developing the capacity of climate change adaptations and the robust water management plans. The findings are anticipated to serve the decision-makers and private sectors to develop strategies for increasing agricultural production and water conservation in the Usangu Plains, southern highlands of Tanzania.

1.3 Study Objectives

1.3.1 Main objective

The main objective of the Study was to model groundwater-surface water interactions and groundwater recharge dynamics in the Usangu Plains, Tanzania.

1.3.2 Specific objectives

The specific objectives of the Study included to:

i. Evaluate the groundwater recharge dynamics in the Usangu Plains
ii. Analyze the processes of water exchanges between groundwater and surface water
iii. Evaluate future climate change influence on groundwater recharge dynamics

1.4 Conceptual Framework

The GIS-based WetSpass (Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State) model, used to simulate groundwater recharge dynamics and future climate change influence on groundwater recharge, functions depending on groundwater levels, topography, land use, soil texture, slope, precipitation, wind speed, potential evapotranspiration and temperature factors (Batelaan and De Smedt, 2007). Groundwater-surface water interactions were analyzed using three hydrograph separation techniques, its conceptual framework is clearly described in the methodology section of the second objective.

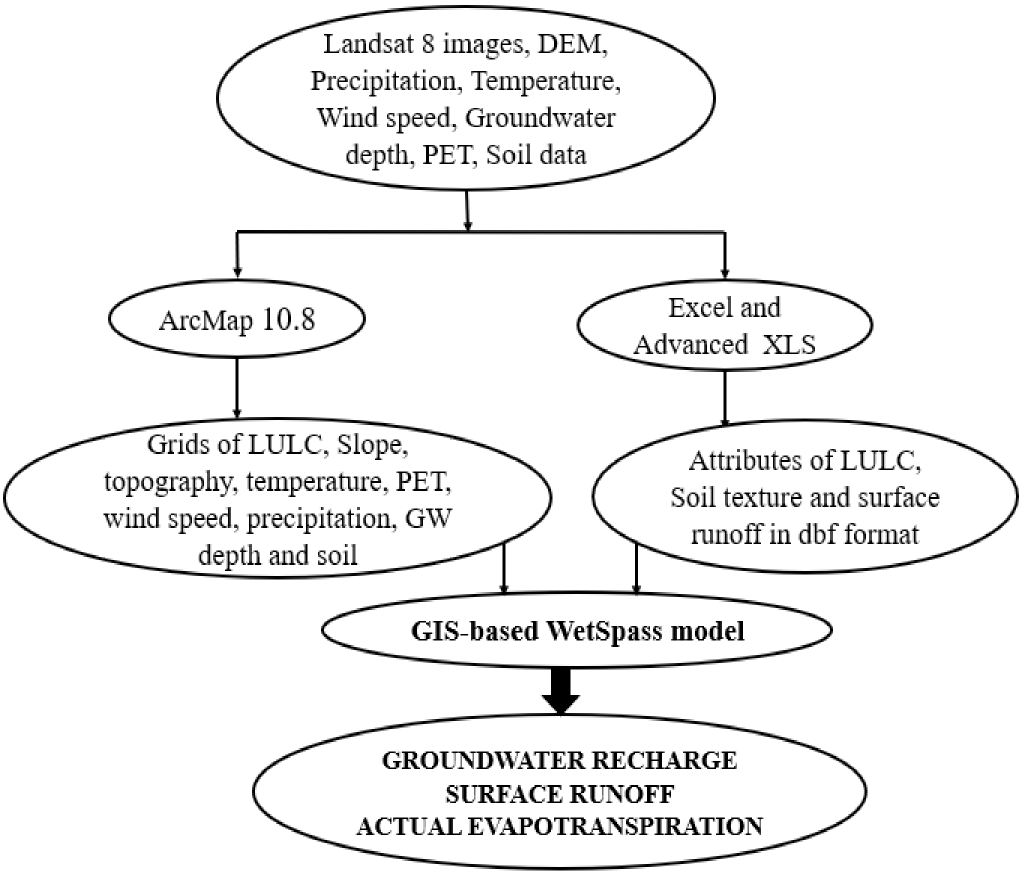

Figure 1.1: Conceptual framework for the WetSpass model (source: own processing)

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CHAPTER TWO

2.0 Evaluation of groundwater recharge dynamics using the WetSpass Model in the Usangu Plains, Tanzania.

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2.1 Abstract

A comprehensive understanding of groundwater recharge dynamics is of great importance in enhancing the sustainable management of the groundwater resources and the sound planning of their utilization. This study evaluated the groundwater recharge dynamics in the Usangu Plains (20 810 km^2) using a GIS-based hydrological model called WetSpass. The inputs of the Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi-Steady State (WetSpass) model were grids of land use/landcover, soil texture, topography, slope, groundwater table, potential evapotranspiration, wind speed, precipitation and temperature prepared in the GIS environment. WetSpass simulated the temporal averages and spatial differences of groundwater recharge, surface runoff and actual evapotranspiration. The findings showed that 13.1% of the mean annual rainfall contribute to the groundwater storage while 76.8% and 14.5% are lost through evapotranspiration and surface runoff, respectively. The groundwater recharge zone with the lowest recharge rates (0-72 mm/year) occupied 40% of the total Usangu Plains area, the zone receiving the moderate recharge rates (73-209 mm/year) has 45% while the zone with the highest rates (210-481 mm/year) occupied 15%. Due to the paucity of groundwater withdrawal information in this study, approximately 10% (0.22 km^3/year) of the annual recharge (106 mm/year) was tentatively adopted to be the groundwater that can be cautiously extracted for human and economic purposes. Compared to the water lost through evapotranspiration and surface runoff, the simulated portion of groundwater recharge is noticeably low. Consequently, it could be wise to initiate artificial groundwater recharge strategies particularly in the zones with moderate and low recharge rates to boost the groundwater storage.

Key words: groundwater safe yield, recharge dynamics, WetSpass Model

2.2 Introduction

Groundwater is an important natural resource that forms components of the hydrologic cycle with vital contributions to the economic development and environmental sustainability (Bhanja *et al.*, 2018). It sustains the ecosystems through maintenance of rivers while stabilizing land in areas with soils that are easily compressed (Foster, 2016). Groundwater quantification underpins the water resources management and utilization. Though the groundwater is mainly lost through human withdrawals, surface water bodies and evapotranspiration, its storage is replenished by groundwater recharge (Nyagwambo, 2006). Groundwater can be recharged directly from precipitation, locally from depressions and rivulets, indirectly from rivers, irrigation losses (Vries and Simmers, 2002), urban recharge and intermediate recharge (Scanlon *et al.*, 2002).

For irrigation purposes, groundwater is readily available, more suitable in quality than surface water and naturally sheltered from direct surface contamination by anthropogenic actions (Fenta *et al.*, 2014). However, the comparative advantages of groundwater over surface water have not been adequately tapped. Scanlon *et al.* (2006) indicated that there is a gap of knowledge concerning temporal and spatial distribution of groundwater recharge across Africa.

In Tanzania, the knowledge gap is partly caused by limited aquifer data as reported for major aquifers (Mahoo *et al.*, 2015). Consequently, limited information is available on the estimates of recharge flux for diverse aquifers in Tanzania. There is a need to conduct studies on groundwater recharge dynamics for different aquifers. Groundwater recharge dynamics are very essential for the water resources management strategies. In Tanzania, there are no extensive studies on groundwater recharge dynamics, hence the recharge rates are not well known (Kashaigili, 2010). Due to the increasing irrigation water demands in the Usangu Plains and the anticipated shifts of water withdrawal towards groundwater, the assessment of groundwater recharge dynamics is recommended for better understanding of its spatial and temporal distribution for its efficient use.

Diverse methods have been used for the groundwater recharge quantification (Scanlon *et al.*, 2002). The methods can generally be categorized into numerical modelling, physical techniques, water balance approaches, chemical tracing, streamflow analysis and many more (Huet *et al.*, 2016). For the spatial and temporal evaluation of groundwater recharge, the numerical modelling approaches have been appreciated by many researchers for the accurate, reliable, and rapid estimations (Arshad *et al.*, 2020; Batelaan and De Smedt, 2007; Hailu *et al.*, 2018; Kashaigili *et al.*, 2006b; Maréchal *et al.*, 2006; Meresa and Taye, 2019; Wahyuni *et al.*, 2008). Among numerical modeling approaches, the use of Geographical Information System (GIS)-based models is adequate in handling the spatial and temporal variability (Tilahun and Merkel, 2009). In particular, the Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi-Steady State (WetSpass) model has been used to evaluate the temporal averages and spatial differences of groundwater recharge on a seasonal and annual basis. The advantages of the WetSpass model over other models in groundwater recharge estimation includes the integration of the GIS and the hydrological processes. This study is designed to analyze the groundwater recharge dynamics of the Usangu Plains aquifer using the GIS-based WetSpass model. Specifically, the study intended to (1) determine the water budget components, (2) investigate the groundwater recharge zones and (3) evaluate the quantity of groundwater that can be extracted safely from the Usangu Plains aquifer for irrigation, domestic use, and livestock to enhance the sustainable management of the water sources.

2.3 Materials and Methods

2.3.1 Description of the study area

The study was conducted in Usangu plains, Tanzania (Figure 2.1). The area is located at an average elevation of 1100 m above mean sea level (a.m.s.l). The area is encircled by the Kipengere, Poroto and Chunya mountains with an elevation reaching 3000m amsl. The Usangu Plains cover an area of approximately 20 810 km^2 (Kadigi *et al.*, 2004) and lie between latitudes 7º41' and 9º25' South and longitudes 33º40' and 35º40' East. Its climate is mostly influenced by the air mass movements together with inter-tropical convergence zone (Kashaigili *et al.*, 2006a). The Usangu Plains' rainfall regime is unimodal, having one wet season from December to June, with some irregularities, the rainfall distribution varies spatially and is very localized depending on the altitude (Kashaigili *et al.*, 2006a). The mean annual rainfall is between 1000 and 1600 mm within the highlands while the central plains, formed of dry fans and wetlands ecosystems, receives 500-700 mm (Malley *et al.*, 2009).

The Usangu Plains' mean annual temperature is between 18ºC and 28ºC in the highlands and lower parts, respectively and its mean annual potential evapotranspiration goes up to 1900mm (SMUWC, 2001). The land vegetation cover differs from the high to the low altitudes, where between 2000m and 1100m amsl are dominated by the miombo woodland and below 1100m amsl are the fans, the wetland ecosystems and agricultural lands (SMUWC, 2001). The high increase of population and the expansion of anthropogenic activities within and in the vicinity of the wetlands have caused the extreme water demand. In both dry and wet seasons, there are water demand for irrigation, domestic use, livestock, brickmaking, and hydropower generation which is the major water user though taking place a long way downstream (SMUWC, 2001).

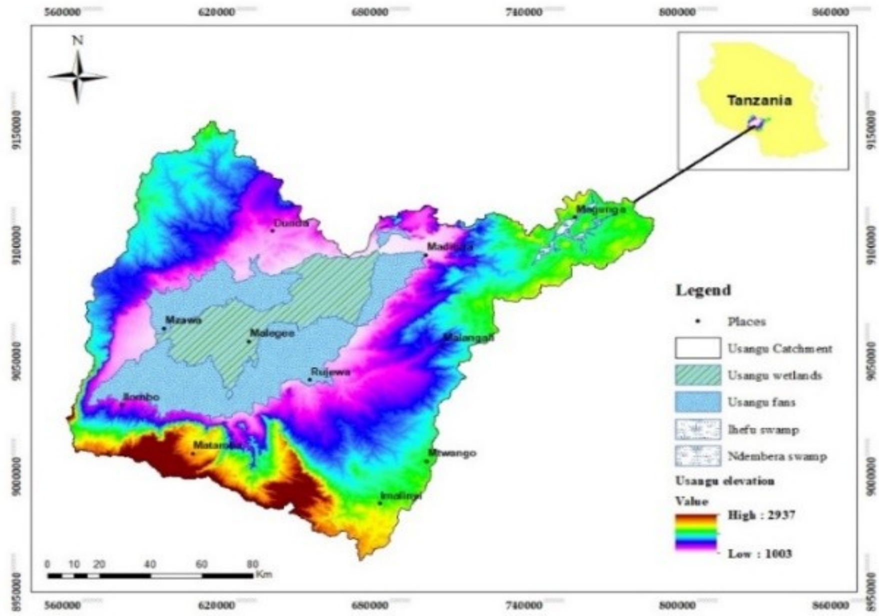

Figure 2.1: Map of Usangu Plains showing topography, fans, wetlands and swamp

2.3.2 Description of the WetSpass model

The WetSpass model is used to evaluate the groundwater recharge dynamics in the Usangu plains. The model is meant to simulate the temporal average and spatial differences of groundwater recharge, surface runoff and actual evapotranspiration. WetSpass stands for Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State (Batelaan and De Smedt, 2007). This model is fully integrated in the GIS ArcView (version 3.2) as raster model, coded in Avenue (Batelaan and Woldeamlak, 2003). WetSpass is a steady state spatially distributed and physically based water balance model. It simulates yearly and seasonal long-term average spatial patterns of the water budget components by employing physical and empirical relationships. Inputs for this model include grids of land use, groundwater depth, precipitation, potential evapotranspiration, wind-speed, temperature, soil, topography, and slope whereby parameters such as land-use, surface runoff and soil types are connected to the model as attribute tables of their respective grids.

Given that WetSpass is a distributed model, the water balance calculation is executed at a raster cell level. Individual raster water balance is obtained by summing up independent water balances for the vegetated, bare soil, open water, and impervious fraction of a raster cell (Figure 2.2). The total water balance of a given area is thus calculated as the summation of the water balance of each raster cell (Batelaan and De Smedt, 2007).

Concerning a vegetated area, the water balance depends on the average seasonal precipitation (P), interception fraction (I), surface runoff (S_v), actual transpiration (T_v), and groundwater recharge (R_v) all with the unit of [LT^{-1}], referring to the equation given below:

$P = I + S_v + T_v + R_v$. ……………………………………….…………………........……(1)

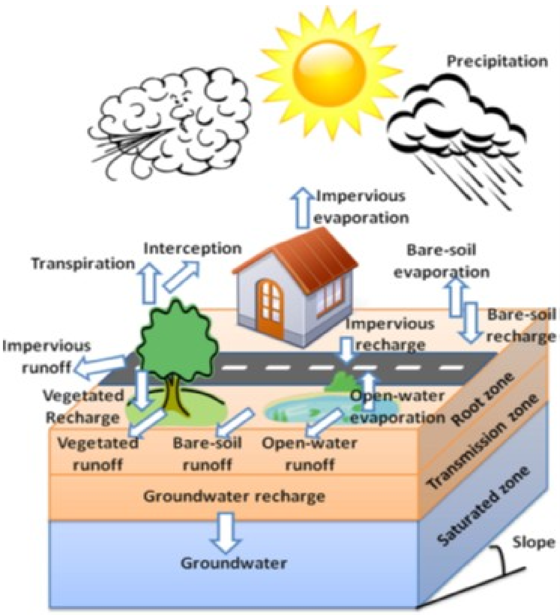

Figure 2.2: Schematic representation of water balance for a hypothetical landcover grid cell (Batelaan and De Smedt, 2007)

Firstly, the interception (I) portion represents a constant percentage of the annual rainfall value, depending on the type of the vegetation. Hence, the fraction declines with an increase in an annual total precipitation amount.

Secondly, the computation of the surface runoff is related to the amount of precipitation, its intensity, interception and soil infiltration. The surface runoff is calculated in two steps:

a) Initially, the potential surface runoff ($S_{v\text{-}pot}$) is calculated as follows:

$$S_{v\text{-}pot} = C_{sv}(P-I) \quad (2)$$

Where, C_{sv} is a surface runoff coefficient for vegetated infiltration areas, and is a function of vegetation, soil type and slope. P is the average seasonal precipitation [LT^{-1}] and I is the interception fraction [LT^{-1}].

b) In the second step, the actual surface runoff is calculated from the $S_{v\text{-}pot}$ by considering the differences in precipitation intensities related to the soil infiltration capacities.

$$Sv = C_{HOR}Sv\text{-}pot \quad (3)$$

Where C_{HOR} is a coefficient for parameterizing that part of a seasonal precipitation contributing to the Hortonian overland flow.

To calculate a seasonal evapotranspiration, a transpiration reference value is obtained from open water evaporation and a vegetation coefficient:

$$T_{rv} = cE_o \quad (4)$$

Where T_{rv} is the reference transpiration of a vegetated surface [LT^{-1}], E_o the potential evaporation of open water [LT^{-1}] and c the vegetation coefficient [dimensionless]. This vegetation coefficient (c) can be calculated as the ratio of reference vegetation transpiration to the potential open-water evaporation as given by the Penman-Monteith equation:

$$C = \frac{1 + \frac{\gamma}{\Delta}}{1 + \frac{\gamma}{\Delta}\left(1 + \frac{r_c}{r_a}\right)}$$

………………………………………………………………………. (5)

Where: γ = psychrometric constant [$ML^{-1}T^{-2}C^{-1}$],

Δ = slope of the first derivative of the saturated vapor pressure curve (slope of saturation vapor pressure at the prevailing air temperature) [$ML^{-1}T^{-2}C^{-1}$],

r_c = canopy resistance [TL^{-1}] and

r_a = aerodynamic resistance [TL^{-1}] given by

$$r_a = \frac{1}{k^2\ U_a}\left(\ln\left(\frac{Z_a - d}{Z_0}\right)\right)^2$$ ………………………..

…………………………………………...(6)

Where: k is the Von Karman constant (0.4) [dimensionless],

U_a is the wind speed [LT^{-1}] at measurement level Za (height above the ground) = 2m,

d is the zero-plane displacement length [L] and

Z_o is the roughness length for the vegetation or soil [L].

Lastly, the groundwater recharge for vegetated area is then calculated as a residual term of the water balance taking into account the above three components,

$R = P - S_v - ET_v – I$ ……………………………………………………………………..(7)

R is the groundwater recharge, P is the precipitation, S_v the surface runoff, ET_v is the actual evapotranspiration and I the interception fraction, all with the unit [LT^{-1}].

The same process as that of the computation for the vegetated area is followed to calculate the water balance for bare soil, impervious areas, and open water. Due to the absence of vegetation in these places, the ET_v becomes E_s (bare soil evaporation) for there is no transpiration and interception components.

Using the water balance components of vegetated, bare soil, open water and impervious areas, the total water balance of a raster cell is therefore calculated as illustrated in the equations 8, 9 and 10:

$ET = a_v ET_v + a_s E_s + a_o E_o + a_i E_i$ ……………………………………………………………(8)

$S = a_v S_v + a_s S_s + a_o S_o + a_i S_i$ ……………………….……………………………………(9)

$R = a_v R_v + a_s R_s + a_o R_o + a_i R_i$ …………………………...…………………………...(10)

Where ET, S and R are the total evapotranspiration, surface runoff, and groundwater recharge of a raster cell respectively, each having a vegetated, bare soil, open water and impervious area component denoted by a_v, a_s, a_o, and a_i, respectively. The letters v, s, o and i represent vegetated, bare soil, open water and impervious area, respectively.

2.3.3 Description of input data for WetSpass model

As the WetSpass model necessitates seasonal-based parameters, seven months (December, January, February, March, April, May and June) are considered as wet (winter) season and the remaining five months (from July to November) as dry (summer) season for the case of Usangu Plains (Kashaigili *et al.*, 2006a). The inputs data were prepared in the form of grid maps using ArcGIS software version 10.8 and parameter tables were edited in Microsoft Excel 365 and converted to dbf format by Advanced XLS Converter. The grid maps were of land-use, soil texture, slope, topography, groundwater levels, precipitation, potential evapotranspiration, temperature, and wind speed. The cell size of grid maps was 30m by 30m and had 7646 columns and 6345 rows. The grid maps were prepared through the ArcGIS environment using Inverse Distance Weigh (IDW) interpolation method. The nearest and bilinear resampling techniques were used to set, respectively, continuous (all weather parameters) and discrete (soil) grid maps to the same resolution (30m). The input files prepared as parameter tables were summer and winter land use, soil texture and runoff coefficient. The runoff parameter table contains runoff coefficients for land use, soil type and slope angles. The natural break slice method in the ArcGIS environment was used to investigate the recharge zones.

2.3.3.1 Hydrometeorological inputs

Daily rainfall data from four ground-based meteorological stations (Msembe, Igawa, Matamba and Kimani) were sourced from the Rufiji Basin Water Board (RBWB), however these data were few to be interpolated for the vast area like Usangu Plains (20 810 km^2). Consequently, this study used regional meteorological data provided by the NASA POWER version 1.0 last modified in 2019/12/19 [*https://power.larc.nasa.gov/ data-access-viewer/*; site visited on 05/03/2021] and the Climatic Research Unit (CRU) [*https://crudata.uea.ac.uk*; site visited on 12/03/2021]. The collected data from the NASA POWER for the Usangu catchment boundary were precipitation, dew point, temperature (maximum and minimum) and wind speed at 2m of height from the soil surface while those sourced from the CRU were for rainfall only. Due to the overestimation of NASA POWER rainfall data, CRU rainfall data were used instead. The comparative analysis of NASA POWER, CRU and the four observed stations data is found in Appendix 1.

These gridded regional data ranging from 01/01/2000 to 31/12/2017 (on a daily timescale) are interpolated to 0.5 degrees (approximately 50 km) of spatial resolution and were averaged to seasonal basis for the sake of the WetSpass model requirements. Solar radiation was derived from temperature using the Hargreaves' radiation formula. The daily extraterrestrial radiation values from Allen *et al.* (1998) were averaged to get monthly figures, given that Usangu plains are located in the southern atmosphere between 7 and 10 degrees of latitude. The actual evapotranspiration was computed through the Instat computer package which uses the FAO-Penman Monteith equation, as it is globally recommended for calculating the evapotranspiration (Rwebugisa, 2008). For the WetSpass requires meteorological inputs in the grid format on a seasonal basis, the IDW interpolation method in the GIS environment was used to prepare the grid maps of precipitation, temperature, wind speed and evapotranspiration; both for wet and dry seasons.

Table 2.1: The summary of meteorological data used (source: own processing)

Parameter	Season	Minimum	Average	Maximum
Precipitation (mm)	Wet	619	754	899
	Dry	41	105	88
	Annual	659	812	987
Temperature (C)	Wet	17.99	20	21.66
	Dry	18.04	20	23.09
	Annual	18.01	19.90	22.37
Wind speed (m/s)	Wet	0.70	1.00	1.88
	Dry	1.18	2.00	3.00
	Annual	0.94	1.69	2.44
Evapotranspiration (mm)	Wet	651.7	728	808.9
	Dry	582.7	710	850.6
	Annual	1234.4	1438.2	1659.5

Groundwater (GW) level fluctuation data were obtained from the RBWB. Six years, ranging from 2015-2020, daily groundwater level data of six boreholes were availed. The IDW interpolation technique of the ArcGIS Desktop10.8 environment was used to generate the grid maps of the wet and dry seasons of GW depths. The adoption of mean GW depths does not influence the WetSpass simulation results if the GW depths in the study area are more than the root depths (Tilahun and Merkel, 2009).

2.3.3.2 Areal-based biophysical inputs

i. Topography and slope

For slope and topography data, digital elevation model (DEM) of the study area was extracted from the Shuttle Radar Topography Mission (SRTM) available on the United

States geological survey (USGS) earth explorer website [*https://earthexplorer.usgs.gov/*; site visited on 19/03/2021] at a spatial resolution of 30m. With the Usangu basin boundary, its raster was clipped from the combined satellite images.

The clipped raster of Usangu was used to create elevation and slope grid maps of the Usangu Plains using spatial analyst tools, considering the year 2017 for spatial data. The elevation ranges from 1003m to 2956m above mean sea level with an average of 1429m and the slope varies from 0% to 74%.

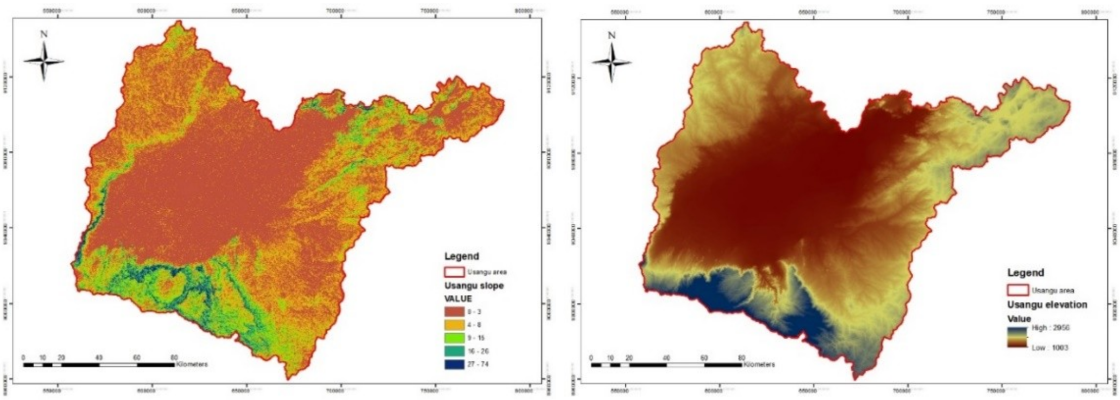

Figure 2.3: Slope map (left) and topographic map (right) of Usangu Plains

ii. Soil texture

Soil textural information is an important input of the WetSpass model for the recharge quantification. As far as this study is concerned, the soil data were obtained from the FAO-UNESCO [*http://www.fao.org/geonetwork/srv/en/metadata.show%3Fid=14116*; site visited on 24/03/2021] digitized (vector dataset) soil map of the world at a scale of 1:5 000 000. ArcGIS software was used to clip the soil textural map of the Usangu Plains from the digital soil map of the world. The attribute table of soil textures of Usangu was adjusted using the Soil Water Characteristics program developed by United States Department of Agriculture (USDA) Agricultural Research Service [*http://hydrolab.arsusda.gov/ soilwater/Index.htm*; site visited on 29/03/2021]. The textural classes were found to be clay (24%), clay loam (32%), sandy clay loam (13%), loamy sandy (3%) and sandy loam (28%). The soil classes outputs of this program were validated based on the soil textural triangle.

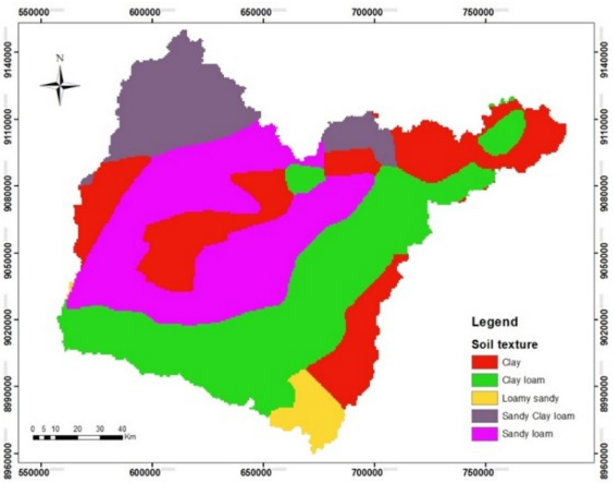

Figure 2.4: Soil texture map of the Usangu plains

iii. LULC classification

Land use/land cover data were processed based on Landsat 8 images of the year 2017 extracted from the United States geological survey (USGS) earth explorer website at a spatial resolution of 30m. Usangu catchment covers three different paths and rows, the periods of the Landsat images used in the area of interest and their respective rows and paths are given in Table 2.2. Land use classification was made using Random Forest classifier in the R-Studio software after performing a supervised classification in ArcGIS environment to generate the spectral classes (regions of interest, ROI). The classification accuracy assessment was executed based on the Google Earth pro truths of the Usangu catchment boundaries. The overall classification accuracy was 82.5% while the overall Kappa statistics was 83.2%. Normally, the land use/ land cover classification accuracy assessment results in this study are satisfactory, for the kappa statistics greater than 80% represent strong accuracy between the performed classification and ground truth information (Ramita *et al.*, 2009).

Table 2.2: Characteristics of the Landsat 8 images of the Usangu Plains

Period	Path	Row
2017-05-02 / 2017-05-15	168	066
2017-11-17 / 2017-11-22	169	066
2017-11-17 / 2017-11-22	169	065

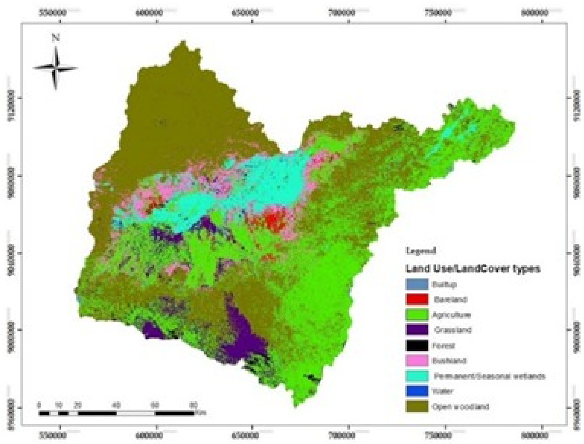

Figure 2.5: LULC maps of the Usangu Plains

2.4 Results

2.4.1 Water budget components of the Usangu plains

2.4.1.1 Surface runoff

The spatial mean annual surface runoff estimated by the model is presented in Figure 2.6. Seasonal and annual average values of surface runoff are illustrated in Table 2.3 in comparison with the annual average rainfall. The annual surface runoff simulated by the model varies from 0 to 739 mm with an average of 118 mm which represents 14.5% of the annual mean rainfall (812 mm). About 87.3% (103 mm) of the mean annual surface runoff occurred in the wet season while the remaining 12.7% (15 mm) happened during the dry season. The maximum amount of annual average surface runoff (592-739 mm) takes place in the built-up and in bare land vegetation types given the impervious state of their ground surfaces. On the other hand, the minimum runoff (0-70 mm) occurred in sandy loam and loamy sandy soil types (Figure 2.6 and 2.7).

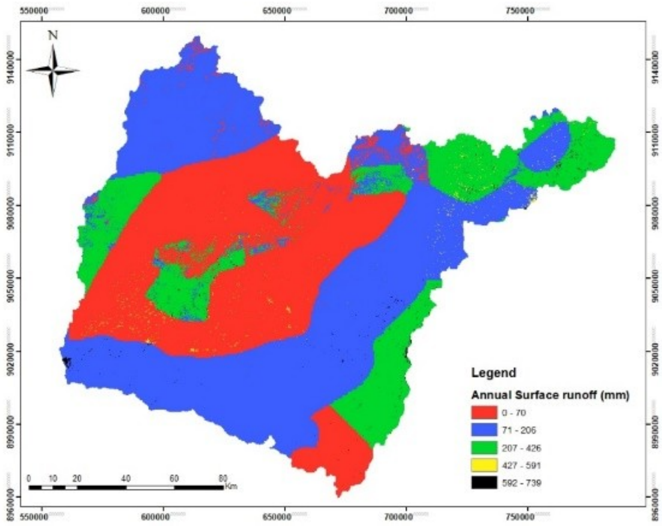

Figure 2.6: Map of annual average of SR in Usangu

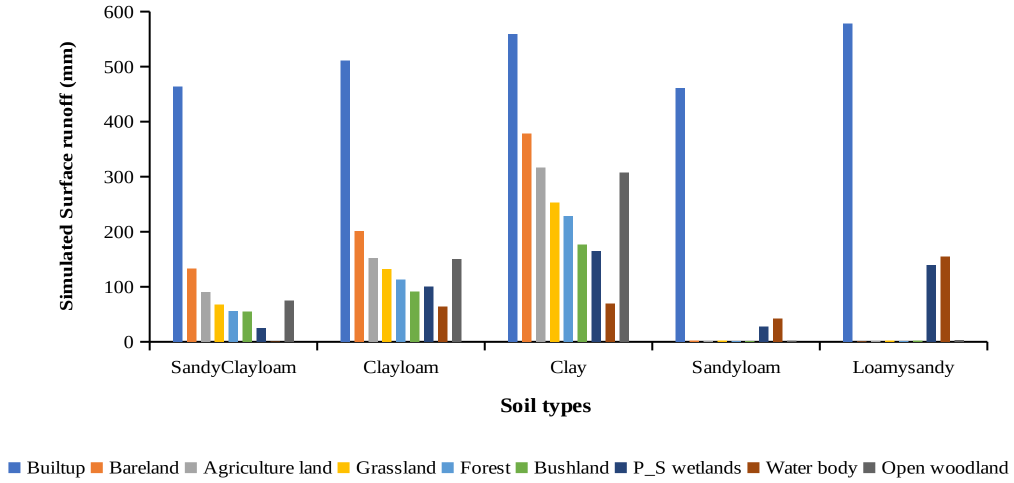

Figure 2.7: Simulated mean annual SR for combinations of LULC and soil texture

2.4.1.2 Evapotranspiration

The WetSpass model computed the total actual evapotranspiration (AET) as a sum of evaporation from the bare soil within land cover types, evaporation from rainwater intercepted by vegetation, evaporation from open water bodies and transpiration from the vegetation canopy. The simulated annual AET map for the results presented in Figure 2.8 and compared to the mean annual precipitation in Table 2.3.

Table 2.3: Water budget components of Usangu simulated by the WetSpass model

Parameter	Precipitation	AET	Surface runoff	Recharge
Dry (mm)	105	97	15	-13
Wet (mm)	754	527	103	119
Annual (mm)	812	624	118	106

The annual average AET is 624 mm which represents 76.8% of the annual rainfall (Table 2.3), 84.5% (527 m) of the mean annual evapotranspiration occurred in the wet season whereas 15.5% (97 mm) happened in the dry season. The maximum evapotranspiration took place in the seasonal/permanent wetlands and water body (Figure 2.9). The next highest values of evapotranspiration occurred in the forest, this is because of the high transpiration and evaporation from the intercepted water. The lowest values are from open woodland and built-up.

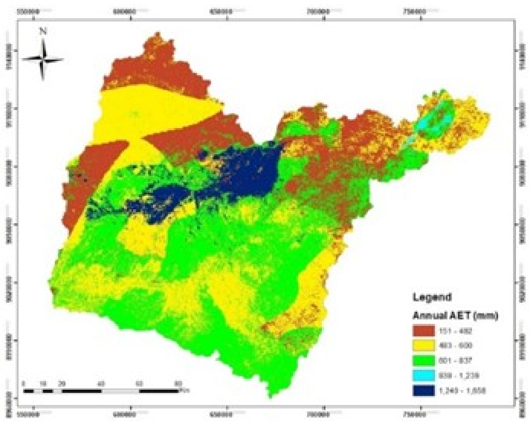

Figure 2.8: Map of annual average of AET in Usangu Plains

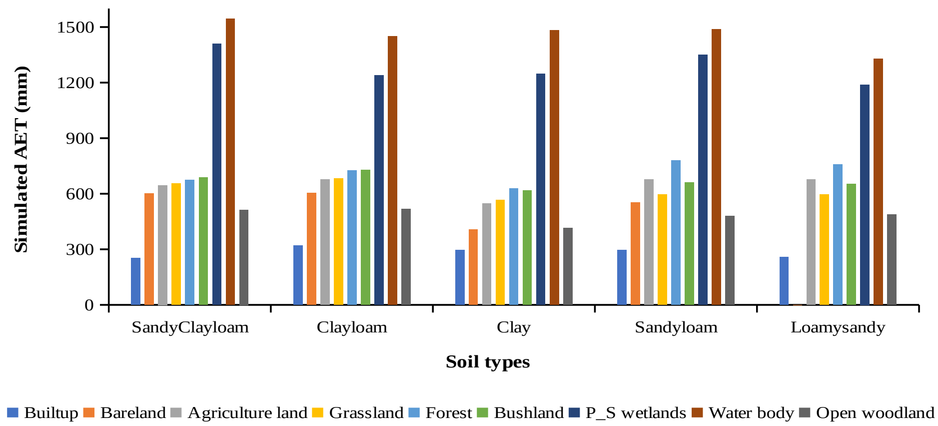

Figure 2.9: Simulated mean annual AET for combinations of LULC and soil texture

2.4.1.3 Groundwater recharge

The average long-term annual groundwater recharge in the Usangu plains simulated by the WetSpass model is presented in Figure 2.10 with comparison to the annual average precipitation in Table 2.3. The simulation results proved the spatial and temporal variations of the groundwater recharge process within the area. The recharge dynamics depend much on the hydrometeorological conditions, land use/landcover composition and soil textures. The model results for the wet, dry, and annual average recharge are 119 mm, -13 mm and 106 mm, respectively. This temporal variation of recharge is caused by the reason that during dry season there is high evapotranspiration compared to the precipitation. The fact that the mean dry season recharge reached a negative value of -13mm indicated the absence of groundwater recharge. Therefore, about 13.1% (106 mm) of the annual average recharge represents the contribution of the rainfall to the groundwater storage. As the Figure 2.11 illustrates, the highest annual values of recharge occurred in all soil classes covered by open woodland but specifically in loamy sandy and sandy loam soil types. The lowest recharge values appeared in clay soils covered by wetlands, bare land and water body; and sandy clay loam soils covered by water body.

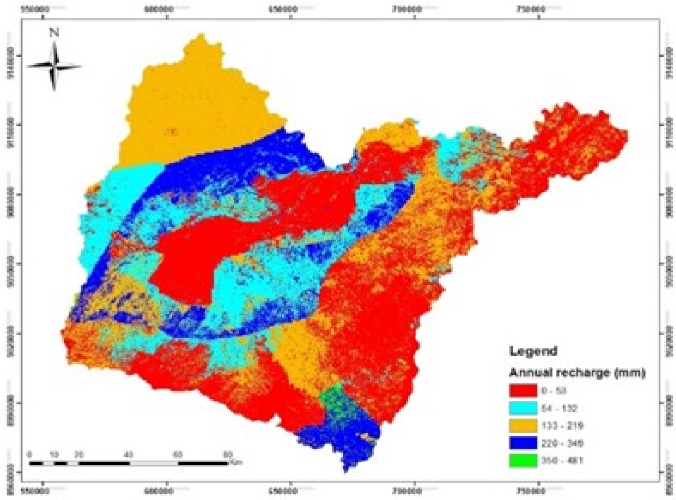

Figure 2.10: Map of annual average of recharge in Usangu Plains

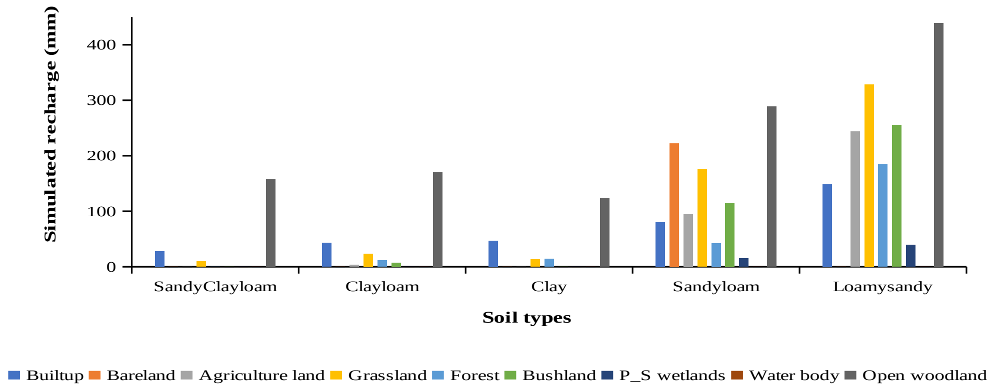

Figure 2.11: Simulated mean annual recharge for combinations of LULC and soil texture

2.4.2 Groundwater recharge zones of the Usangu plains

Ensuing the total annual groundwater recharge, the potential recharge zones in the Usangu Plains are illustrated in Figure 2.12. There were three zones of recharge with different rates (0-72 mm/year, 73-209 mm/year and 210-481 mm/year). The groundwater recharge zone with the lowest recharge rates occupied 40% of the total Usangu area, the zone receiving the moderate recharge rates has 45% while the zone with the highest rates occupied 15%.

On Figure 2.12, groundwater recharge is mostly happening in the southern part and in some zones of the north-eastern and north-western places. The moderate recharge rates occurred in the northern and some central zones of the area. The lowest rates are located majorly in the central and southwestern zones of the Usangu catchment.

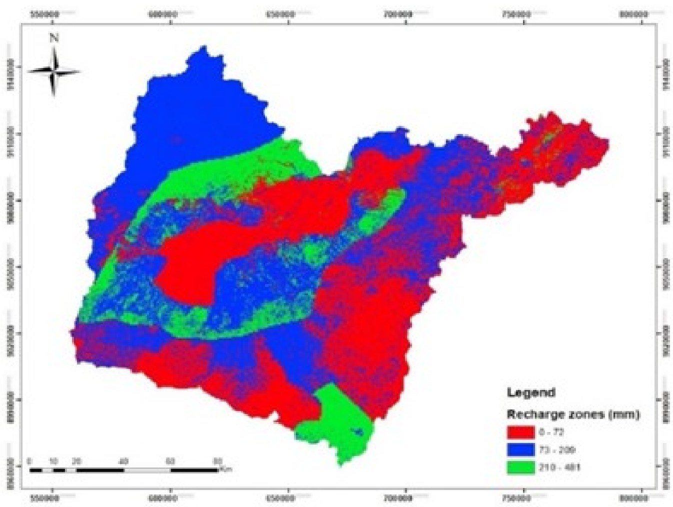

Figure 2.7: Groundwater recharge zones of the Usangu Plains

2.4.3 Groundwater safe yield of Usangu plains

The term safe yield of groundwater in a catchment is used when determining the amount of water that can be extracted from the catchment without depleting the storage (Meyland, 2011). Safe yield is considered as percentage of groundwater recharge; moreover, a number of authors suggest different percentages of safe yield, from the least conservative (100%) to the reasonably conservative (10%) (Gebreyohannes *et al.*, 2013). This concept implies the sustainable groundwater management to the extent of not exceeding the annual recharge and remain within the safe level of groundwater utilization (Russo *et al.*, 2014). Practically, the sustainable yield of groundwater of more than 10% of annual recharge requires to account for the groundwater-dependent ecosystems (Zeabraha *et al.*, 2020). Three studies done in Ethiopia (Gebreyohannes *et al.*, 2013; Meresa and Taye, 2019; Zeabraha *et al.*, 2020) adopted the safe yield of 25% of recharge. However, this value might not be reliable if not supported by groundwater withdrawal data analysis (Meyland, 2011).

Consequently, the probable value of safe yield of 10% of the mean annual recharge may be tentatively adopted for the Usangu plains due to the lack of groundwater withdrawal information during this study. Therefore, the likely groundwater safe yield ranges from 0 to 48.1 mm/year with an average of 10.6 mm/year. Considering the area of Usangu (20 810km^2), 0 to 0.22 km^3/year of groundwater may be cautiously withdrawn for irrigation, domestic use and many more purposes.

2.5 Discussion

The aim of this study was to evaluate the spatial and temporal distribution of the groundwater recharge in Usangu Plains. Table 2.3 summarizes the overall water budget components of the Usangu plains. The WetSpass model showed that 13.1% (106 mm) of the mean annual rainfall contribute to the groundwater storage while 76.8% (624 mm) and 14.5% (118 mm) are lost through evapotranspiration and surface runoff, respectively. Since the water balance is regulated by some factors like precipitation, soil texture and land cover types (Nyagwambo, 2006), the combined method in ArcGIS environment was used to detect the influence of biophysical features on the water budget components.

Surface runoff depends mainly on the availability of land use/landcover types, soil type, rainfall, topography and slope of the area (Batelaan and De Smedt, 2007). As Figure 2.7 illustrates, surface runoff was very high in the clay, clay loam and sandy clay loam soils covered with built-up and bare land because of the less infiltration capacities of the soil types and the imperviousness of the surface cover types similar to the findings of the study done by Zeabraha *et al.* (2020). On the other hand, the minimum surface runoff happened in loamy sand and sandy loam soils covered by forest, open woodland, bushland, agricultural land, grassland, and uncovered soils as a result of the highest permeability of the soils and the high evapotranspiration rate of the land cover types. As SMUWC (2001) reported, a high proportion of vegetation in Usangu reduces the rate of runoff. There was less runoff amount in the lowland compared to the highland of Usangu as depicted in Figure 2.3. The elevation and slope are major factors causing the high surface runoff rate as proved also by Tilahun and Merkel (2009).

The study of Helena (2016) showed a great increase of evapotranspiration in the Usangu catchment in both dry and wet seasons. In addition, the annual precipitation of about 700 mm are generally lost through evapotranspiration in Usangu (SMUWC, 2001). This study found that 624 mm/year are lost by means of AET which is a value close to SMUWC (2001) report’s value (about 700 mm). The high rate of AET occurred in sandy clay loam soil covered by open water sources, then followed clay loam covered by forest. Uncovered loamy sandy soils present low rates (Figure 2.9). AET decreased in the highlands compared to the lowlands of the Usangu Plains because of the high altitudes and low temperature. This decrease of AET in highland can be a factor to enhance agricultural activities during dry season. In agreement with other studies conducted in Usangu catchment and worldwide (Kashaigili *et al.*, 2006a; Rwebugisa, 2008; SMUWC, 2001; Helena, 2016 and Zeabraha *et al.*, 2020), the major factors influencing the actual evapotranspiration are soil texture, land use/landcover types and climate parameters.

SMUWC (2001) defined the lowlands in Usangu catchment as areas below about 1100m of elevation and the remaining areas above 1100m to be the highlands. The same report (SMUWC, 2001) considers the whole zone of highlands as groundwater recharge area. This study found that the highest recharge rate occurred in the south-western highland and slightly above the lowland zones (Figure 2.12), reason being the high altitude. The minimum recharge happened in the lowlands particularly the zones covered by the permanent and seasonal wetlands for they act as discharge zones of the catchment. Figure 2.11 shows the maximum occurrence of recharge in loamy sandy and sandy loam soils covered by open woodland, grassland, bushland, and agricultural land due to the fact that the soil types have good infiltration capacity and the LULC types which reduce surface runoff rate. It is also due to the low rate of evapotranspiration caused by less temperature and high elevation (SMUWC, 2001). A study done in Ethiopia (Meresa and Taye, 2019) indicated that clay soils covered with wetlands, water bodies and clay-based bare lands had low recharge values similar to the findings of this study (Figure 2.12). The comprehensive understanding of potential recharge zones in the Usangu Plains is of paramount benefit for locating areas of conservation.

The study conducted in Dodoma, Makutupora basin, indicated that recharge represents 1-2% of annual rainfall (Rwebugisa, 2008), this is because the area is arid and receives less amount of annual rainfall compared to Usangu Plains. In contrast, 13.1% of annual rainfall in Usangu Plains go to the groundwater reserve. The probable groundwater safe yield was tentatively taken to be 10% of the annual groundwater recharge to account for other groundwater-dependent users as it has been stated by the study conducted in Ethiopia (Zeabraha *et al.*, 2020). The information on the safe yield plays a tremendous role in conserving the groundwater storage, though requires undoubtedly the consideration of groundwater withdrawals to be reliable for decision making. This study agreed that topographic, soil types, land use and land management are driving factors of spatial and temporal recharge dynamics.

2.6 Conclusions and Recommendations

Groundwater usage covers many sectors such as irrigated agriculture, domestic use, industrialization, livestock and many more. Sustainable management of the groundwater storage is vital; however, it requires a clear understanding of the groundwater recharge distribution whether spatially and/or temporally. This study aimed at evaluating the groundwater recharge dynamics in the Usangu plains to help water users and decision makers have a comprehensive understanding of the quantity of recharge that replenishes the groundwater storage. To achieve this aim, the hydrological WetSpass model, which simulates seasonal and yearly long-term average spatial variations and temporal averages of water budget components by utilizing physical and empirical relationships, was used. The model showed that 13.1% of the annual rainfall goes to groundwater storage while 14.5% and 76.8% go to surface runoff and actual evapotranspiration, respectively. Low slopes and a high proportion of vegetation were found to reduce the surface runoff. Open water sources and vegetated soils have high rates of actual evapotranspiration. The model reported the absence of groundwater recharge in the dry season; however, 15% of the total Usangu area receives the high rates (210-481 mm/year) of groundwater recharge in southern zone and some zones of the north-eastern and north-western area. The northern and some central zones of the Usangu Plains are moderately recharged while the lowest recharge rates occurred mainly in the central and southwestern zones. The likely groundwater safe yield of 10% of the total annual recharge was tentatively anticipated allowing 0.22 km^3/year to be cautiously abstracted to mainly support all the water requirements in the Usangu plains. The findings of this study are useful as a base for future groundwater recharge-oriented considerations. Moreover, there must be rigorous regulations for groundwater drilling/extracting entities to not deplete the water storing capacity which may lead to the water usage conflicts. Compared to the water lost through evapotranspiration, the simulated portion of groundwater recharge is obviously low. Consequently, it could be wise to initiate artificial groundwater recharge strategies particularly in the zones with moderate and low recharge rates to boost the groundwater storage as its users cannot cease to increase.

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CHAPTER THREE

3.0 Analysis of water exchange processes between groundwater and surface water in the Usangu Plains, Tanzania

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3.1 Abstract

The groundwater and surface water interface has been proved evident by the existence of effluent and influent streams. Still, the irrigation sector in sub-Saharan Africa, Tanzania included, is predominantly using surface water and groundwater conjunctively without a clear understanding of the contribution of each of the two water resources. A study was conducted in the Usangu Plains to analyze the water exchange processes between groundwater and surface water. Three hydrograph separation techniques (Sliding interval, Fixed interval, and Local minimum) of the Baseflow Index model third version (BFI+ 3.0) were used to estimate the baseflow, surface runoff and the baseflow indices of the river discharge data from six gauging stations of six different rivers. Further, the Mann-Kendall (MK) test was used for trend analysis of the long-term time series baseflow index. Results indicate that the groundwater-surface water interaction exists and the baseflow contributes substantially to the sustainable river flows in the Usangu Plains during both dry and wet seasons. Except for the Great Ruaha River at Msembe, the other five rivers manifested a great reliance on the baseflow with more than 90% of it in the river flows. The MK test revealed that at annual, wet, and dry season scale there are statistically non-significant increasing and decreasing trends in the baseflows. Land and water management strategies such as water allocation measures, sound water usage practices, and afforestation may be better approaches to counteract the declines of water flows in rivers of the Usangu Plains, especially in the dry season.

Key words: baseflow, interaction, rivers, Usangu Plains.

3.2 Introduction

The understanding of groundwater and surface water interaction is vital for the water resources management and sustainable utilization. For many years, groundwater and surface water have been considered as separate components of the hydrological cycle in the application of water management policies (Yang, 2018). In contrast, these two water sources are hydraulically connected (Raz *et al.*, 2017). Groundwater and surface water interactions occur by means of different mechanisms on varying levels and affect the recharge-discharge processes of groundwater and surface water (Sophocleous, 2002). The groundwater and surface water interface has been proved evident where the effluent and influent streams were identified as the proof of that inter-connectedness (Matthews, 2013). Water availability in any catchment relies on the relationship between groundwater and surface water (Mul, 2007).

Globally, groundwater withdrawal has increased from a base level of 100-150 km^3 in 1950 to 950-1000 km^3 in 2000 (Shah *et al.*, 2013). Apart from domestic use, livestock and industries, about 70% of the global freshwater is estimated to sustain the irrigated agriculture which is likely to be the most important water use sector (Siebert *et al.*, 2010). Still, the irrigation sector in sub-Saharan Africa is predominantly using surface water and groundwater conjunctively without a clear understanding of the contribution of each of the two water resources (Siebert *et al.*, 2010). However, groundwater discharges plays a capital role in sustaining surface water bodies (Foster, 2016) especially during dry seasons. Certainly, the knowledge of groundwater and surface water interconnectedness is needed as soon as possible to sustainably manage the available water resource for the betterment of its all users. In Tanzania, as well as other African countries, the quantification of groundwater discharges to surface water sources is challenged by the deficiency of data, technical skills and financial support (Mahoo *et al.*, 2015). These, in addition to ineffective policies, have led to an uncontrolled exploitation of the two water sources for human and economic activities. In the Usangu Plains located in the southern highlands of Tanzania, it was evoked that the increase of groundwater withdrawal may be another possible cause of reducing surface water storage and further studies were recommended for its sustainable management (Kashaigili *et al.*, 2006; Mbaga *et al.*, 2015). Furthermore, the quantification and understanding of the interaction between groundwater and surface water are necessary for the suitable management of riparian ecosystems (Kalbus *et al.*, 2006).

Several authors have applied various methods for identifying and quantifying the amount of surface water being contributed to the aquifers as well as groundwater contributing to wetlands, rivers or lakes by (Huizenga, 2015; Kalbus *et al*., 2006; Madlala, 2015; Matthews, 2013; Sophocleous, 2002). To counteract the data scarcity challenge, a number of studies emphasize on quantifying the river baseflow (Kelly *et al.*, 2019) to determine the contribution of groundwater discharges to rivers. The baseflow time series, though considered to measure groundwater dynamics within a catchment, has an index that reflects the contribution of catchment stores to river discharge (Querner *et al.*, 1997). While baseflow indices are commonly correlated to hydrological, soil and geological properties (Querner *et al.*, 1997), these details are hardly available at appropriate scale in large areas like Usangu Plains. Nevertheless, Stahl *et al.* (2010) advised the streamflow-derived indices to be used as baseflow indices. Benedict (2019) identified the mixing of subsurface baseflow with surface water and recharge of groundwater by river in lower elevation at Ndembera river of the Usangu catchment using the stable isotopic and SWAT (Soil and Water Assessment Tool) model. But the interaction between the two water resources is still limitedly understood specifically in areas with visible streamflow-level declines like Usangu catchment.

The aim of this study was to analyze the water exchange processes between groundwater and surface water in the Usangu Plains. The specific objectives were to (1) separate the groundwater discharges from surface runoff of the river flows, (2) assess the temporal relationship between baseflow and streamflow and (3) analyze the trend of rivers' baseflow indices. We used three hydrograph separation techniques of the Baseflow Index model third version (BFI+ 3.0; Gregor, 2010) to improve the clear understanding of the groundwater and surface water interconnectedness. The results of this study are expected to enhance the sustainable management of the water resources in the Usangu Plains, Tanzania.

3.3 Materials and Methods

3.3.1 Description of the study area

The Usangu Plains are in the upper part of the Rufiji River Basin at an average elevation of 1100 m above mean sea level (a.m.s.l). The area is delimited by the Kipengere, Poroto and Chunya mountains with an elevation reaching 3000m a.m.s.l in the southern highlands of Tanzania. The Usangu Plains cover an area of approximately 20 810 km^2 (Kadigi *et al.*, 2004) and lie between latitudes 7^{o}41' and 9^{o}25' South and longitudes 33^{o}40' and 35^{o}40' East. The Usangu Plains' rainfall distribution varies spatially and is very localized depending on the altitude (Kashaigili *et al.*, 2006). In Usangu catchment, areas below 1100m of altitude are defined as lowlands while areas above 1100m represent highlands (SMUWC, 2001). The mean annual rainfall is between 1000 and 1600 mm within the highlands while the central plains in the lowlands receives 500-700 mm (Malley *et al.*, 2009). Surface runoff originating from the highlands feeds the central plains and seasonally floods the wetlands ecosystem (Tumbo *et al.*, 2015). The Usangu Plains are drained by the Great Ruaha River, with an outlet at a point called NG'iriama, where a rock outcrop acts as a natural dam controlling the flow from the Eastern

Wetland (Kashaigili *et al.*, 2006). Mbarali, Kimani, Chimala and Ndembera rivers, with confluences in the Usangu central Plains, are the major tributaries to the Great Ruaha River (Figure 3.1). These rivers account for 85% of the whole discharge from the rivers of Usangu Plains and have their sources at high elevations given the high amount of rainfall in the highlands (SMUWC, 2001). The main water suppliers to the Eastern Wetland is the Great Ruaha River and the Ndembera River, which flows from the Western Wetland through the constriction at Nyaluhanga, which discharges into it from the north-east, respectively (Kashaigili *et al.*, 2006).

3.3.2 Data source

The river discharges data were collected from the Rufiji Basin Water Board (RBWB) operating from Mbeya region. Streamflow data were recorded from six (6) river flow gauging stations (Table 3.1) such as Chimala at Chitekelo (1KA7A), Great Ruaha at Salimwani (1KA8A), Kimani at Great North Road (1KA9A), Mbarali at Igawa (1KA11A), Ndembera at Ilongo (1KA15A) and Great Ruaha at Msembe (IKA59A). The river discharge data were recorded in m^3/s on a daily resolution at all the gauging stations and the data period ranges from the 01st of January 2010 to the 31st of December 2019. Referring to the SMUWC (2001) report categorizing highlands and lowlands, only Msembe gauging station of the GRR is found in the lowlands with 838m of altitude. Missing data were filled in relying on the hydrological yearbook of 2010-2019 from the Ministry of Water [*https://www.maji.go.tz/pages/articles*; site visited 06/04/2021].

This book covers river discharges of almost all the national basins including the Rufiji Basin where the Usangu Plains are found. Rainfall information used in this study was sourced from the Climatic Research Unit [*https://crudata.uea.ac.uk*; site visited 13/04/2021] on a monthly temporal resolution and 0.5 degrees of spatial resolution.

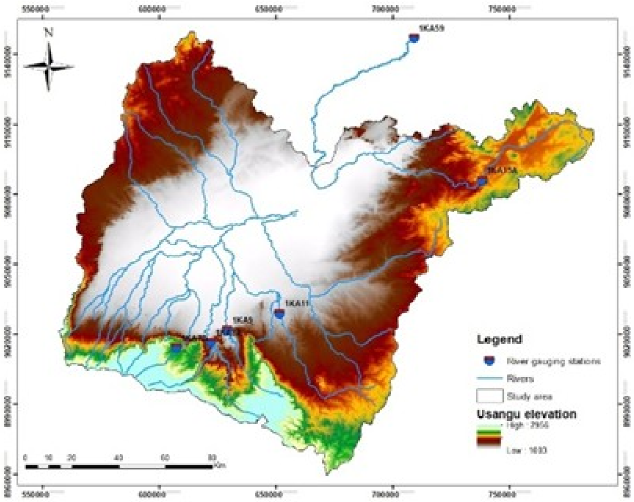

Figure 3.1: Map of the Usangu Plains with river gauging stations and elevation

Table 3.1: River gauging station details

No	Name	Location	Code	Easting (X)	Northing (Y)	Altitude (m)	Area (km^2)
1	Chimala	Chitekelo	1KA7A	607306	9014062	1907	168
2	G. Ruaha	Salimwani	1KA8A	622243	9016503	1152	785
3	Kimani	GNR	1KA9A	629183	9021765	1079	451
4	Mbarali	Igawa	1KA11A	651581	9028846	1119	1553
5	Ndembera	Ilongo	1KA15A	738361	9086002	1673	1105
6	G. Ruaha	Msembe	IKA59A	709328	9146923	838	23527

3.3.3 Methodology

3.3.3.1 Hydrograph separation techniques

With respect to this study, the baseflow separation techniques which assume that streamflow responds to a storm occurrence concurrently with surface runoff were applied to analyze the river discharges. Baseflow Index model third version (BFI+ 3.0) of the HydroOffice 2012 software package was used to estimate the baseflow and surface runoff components of the streamflow (Gregor, 2010). Among its 11 methods, three baseflow separation techniques were chosen for the sake of this study: a) sliding interval method, b) fixed interval method and c) local minimum method. All these techniques use the same formula and approximately the same algorithms which are described in Appendix 1.

$N=(0.8*A)^{0.2}$ (Equation 1) (Gregor, 2010)

where N represents the number of days for the surface runoff and A the river catchment area. The surface runoff duration (N) was calculated based on each river catchment area (Table 3.1). The hydrograph separation techniques used in this study generate baseflow, surface runoff and baseflow index (BFI). The surface runoff was calculated as the difference between baseflow and total river discharge. Annual and seasonal BFI were analyzed to determine the temporal interaction of rivers and baseflow. A comparison among rainfall, river flows and baseflow was performed to confirm the influence of rainfall-driven seasonality on the streamflow variations. The river discharges, baseflow and surface runoff values were converted from m^3/s to mm/month for better comparison. The conversion was made by multiplying the mean monthly cumecs (m^3/s) with 24h, 3600seconds, the number of days of a month and 1000mm, and later dividing the value by the river catchment area (which was converted from km^2 to m^2).

3.3.3.2 Trend analysis

The Mann-Kendall (MK) test was used to analyze the long-term time series baseflow index and determine if there is a statistically significant trend (Table 3.2). The MK test is a non-parametric method built on rejecting or not the null hypothesis which assumes that there is no trend in the data. It has been used by several researchers worldwide and was recommended by the World Meteorological Organization (WMO) to perform trend analysis for hydrometeorological variables (Shu and Villholth, 2012; Kelly *et al.*, 2019; Sobral *et al.*, 2019 and Nagy *et al.*, 2020). This MK test was integrated in the statistical software package named XLSTAT which is a Microsoft Excel Add-In.

Table 3.2: Trend classification for 5% of level of significance (Sobral *et al.*, 2019)

Classes	Code	Scale
Significant increasing trend	+2	Z > 1.96
Non-significant increasing trend	+1	0 < Z > 1.96
No trend	0	Z = 0
Non-significant decreasing trend	-1	-1.96 < Z < 0
Significant decreasing trend	-2	Z < -1.96

Where Z is the Mann-Kendall test statistic

3.4 Results

The total monthly river specific discharges for all the six gauging stations over the period ranging from 2010 to 2019 were used. GRR at Salimwani has the highest value of total flow in the wet seasons with 578 mm in December 2011, with all the flow values below 50 mm in dry seasons except 74 mm in November 2011. It is seconded by Kimani River at GNR having the peak value of 149 mm in January 2016 and the peak of 13 mm in dry seasons; August 2018. The total monthly river flow for Ndembera at Ilongo and GRR at Msembe are below 50 mm while Mbarali river at Igawa is discharging the flow below 100 mm, for both dry and wet seasons. Table 3.3 illustrates the temporal variability of river discharges for the period of 2010 to 2019, where the majority peak values occurred in wet seasons (from December to June) while the lowest flows happened obviously in dry seasons (July to November). Among all the rivers, GRR at Salimwani takes the lead in highest values throughout all the seasons, except from May to September where Chimala river at Chitekelo comes first.

Table 3.3: Mean monthly river specific discharge (mm) for the six river gauging stations

Months	Kimani	Mbarali	Chimala	Ndembera	Salimwani	Msembe
January	60	30	61	16	93	1.6
February	65	34	56	21	85	7.1
March	106	48	79	33	115	7.3
April	77	40	96	32	108	8.7
May	27	20	55	14	50	6.1
June	13	11	35	5	24	2.2
July	8	8	27	2	17	0.8
August	7	6	19	1	13	0.3
September	4	4	13	1	11	0.1
October	3	3	11	0	11	0.0
November	3	4	13	0	17	0.0
December	21	12	25	3	87	0.2

3.4.1 Groundwater discharge separation from total river flow

The baseflow separation techniques used are sliding interval (SI) method, fixed Interval (FI) method and local minimum (LM) method. All are incorporated in the BFI+ tool and use the same Equation 1 though having slightly different algorithms. N, number of days for runoff duration, depends up on the river catchment as Equation 1 indicates. N values in parentheses are rounded off for the model does not accept decimal values.

Table 3.4: River details and N values for each river catchment

No	River Name	Station	Code	Area (km^2)	N Value
1	Chimala	Chitekelo	1KA7A	168	2.66 (3)
2	Great Ruaha	Salimwani	1KA8A	785	3.63 (4)
3	Kimani	GNR	1KA9A	451	3.25 (3)
4	Mbarali	Igawa	1KA11A	1553	4.16 (4)
5	Ndembera	Ilongo	1KA15A	1105	3.88 (4)
6	Great Ruaha	Msembe	IKA59A	23527	6.41 (6)

The total mean groundwater discharges from all the baseflow separation techniques along with the total flow for all the rivers can be seen in Figure 3.2. It is noticeable that the sliding interval method estimated high values compared to fixed interval method. But the local minimum method appeared to show the lowest values of baseflow throughout the period and for all river gauging stations.

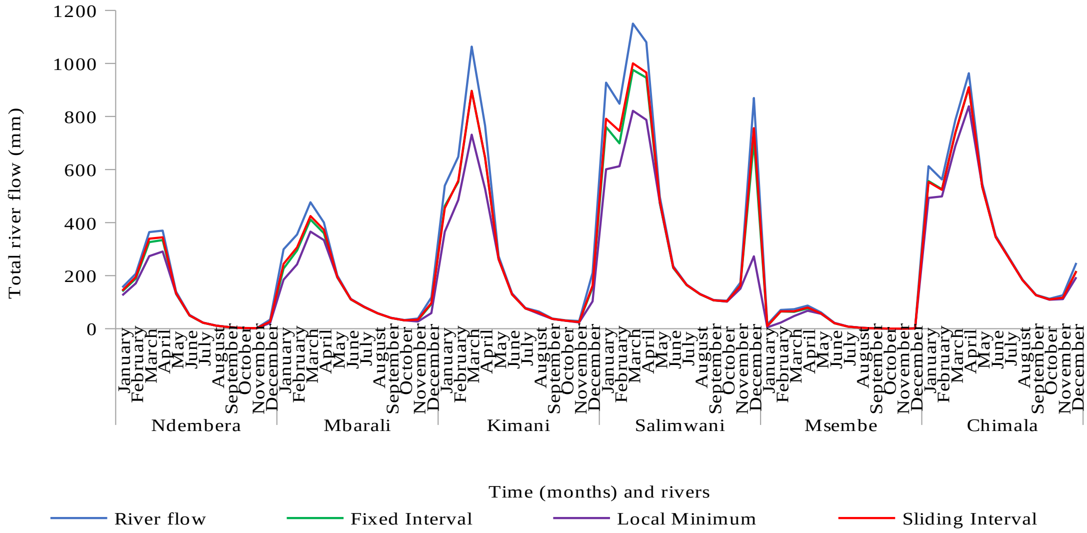

Figure 3.2: Comparison of baseflow separation methods against total river flow

3.4.1.1 Chimala river at Chitekelo

For all the techniques, the baseflow contribution to the river flow happened all over the whole period (2010-2019) in both wet and dry seasons. During rainy season (December to June), the baseflow indices kept on fluctuating downwards and upwards, which implies the contribution of surface runoff and/or the surface water contributions to the groundwater storage. But, through dry season (July to November) the groundwater discharges decreased and the baseflow indices seemed to be somehow stable. Figure 3.3 shows the comparison of different methods of baseflow separation for Chimala river against their respective baseflow indices (BFI_FI: Baseflow Index for Fixed Interval, BFI_LM: Baseflow Index for Local Minimum, BFI_SI: Baseflow Index for Sliding Interval). According to Figure 3.3, it is visible that the sliding interval estimated the highest values of baseflow (1.16% in April 2014) which denoted its great baseflow indices. During the wet seasons, the local minimum estimates less values whereas in dry seasons all techniques tend to estimate almost the same values of baseflow.

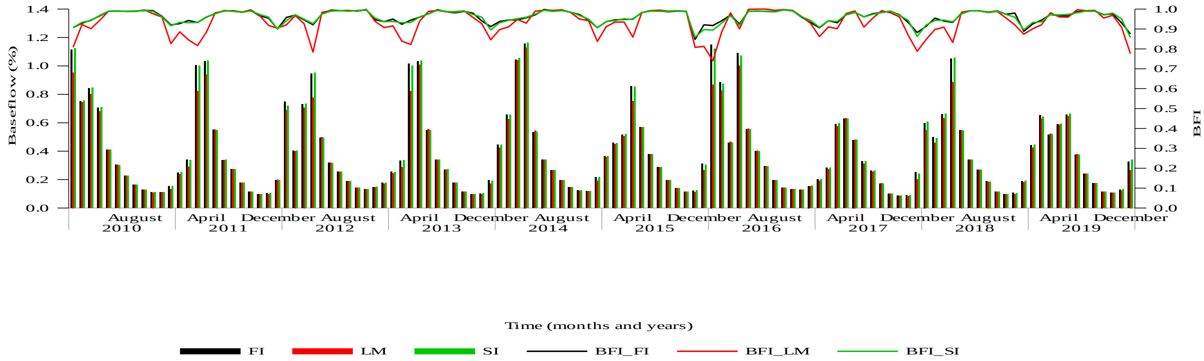

Figure 3.3: Baseflow separation techniques along with BFI for Chimala at Chitekelo

3.4.1.2 GRR at Msembe

The Msembe gauging station is located out of the Usangu plains boundary and has recorded several zero flow values (Table 3.5). This implied the absence of both baseflow and runoff contribution to the river within the no flow periods. However, the results showed that the input of baseflow to the river occurred in both dry and wet seasons during flow periods. The sliding interval method has the highest baseflow estimation (0.43%) in February 2016 as Figure 3.4 represents it. The annual baseflow decreased in 2011 but augmented extremely in 2016.

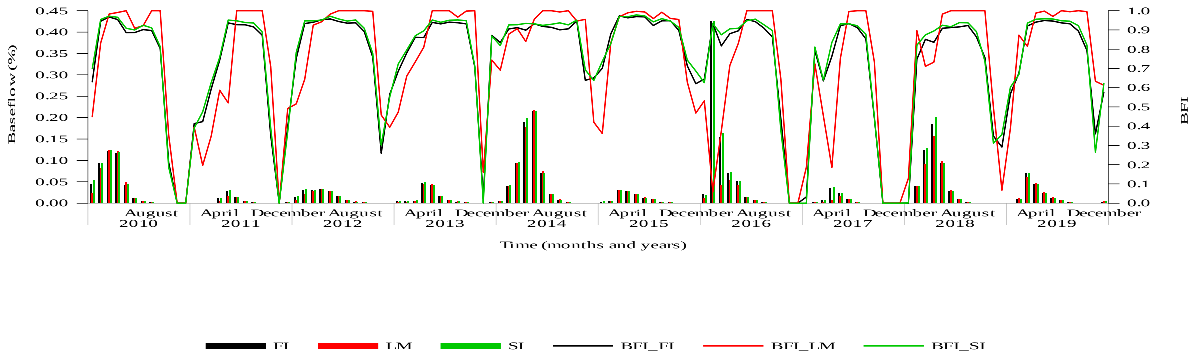

Figure 3.4: Baseflow separation techniques along with BFI for GRR at Msembe

Table 3.5: Periods of zero flow in the Great Ruaha River at Msembe (2010 to 2019)

Year	Flow stopping date	Flow resuming date	Days of no flow
2010	October 12	January 9 2011	90
2011	October 23	December 10	48
2012	November 21	December 11	20
2013	November 3	November 28	25
2016	October 21	January 30 2017*	97
2017	September 23	January 29 2018	127
2018	November 7	November 9	2
2019	November 18	November 29	11

*With some in-between start and stop to flow.

3.4.1.3 GRR at Salimwani

At Salimwani gauging station of the Great Ruaha river, the sliding interval method has high baseflow indices seconded by the fixed interval method. In 2011, there was a high baseflow estimated by all techniques, but sliding method comes first with 5.07% in December 2011 while the local minimum estimated less. From 2011, the groundwater discharges to the river kept on fluactuating seasonally, this was also affecting the baseflow indices as depicted in Figure 3.5.

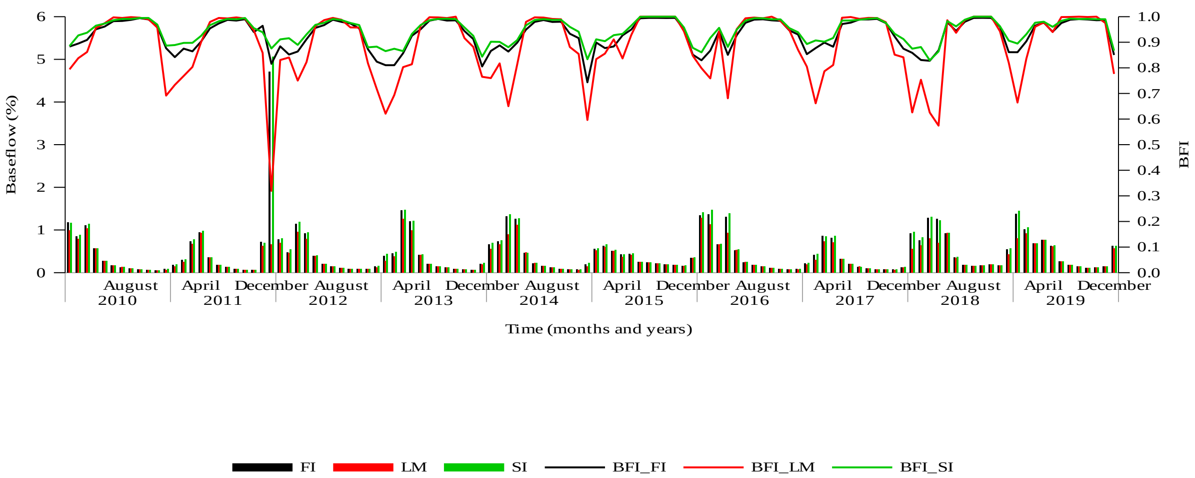

Figure 3.5: Baseflow separation techniques along with BFI for GRR at Salimwani

3.4.1.4 Kimani at GNR

From all the separation methods, the baseflow occurred all along the period and in all seasons. As Figure 3.6 displays, the baseflow indices increased in dry seasons which depicts the contribution of groundwater discharges to the river. However, in wet seasons, the baseflow indices decreased considerably due to the rainfall contribution. Additionally, the peak of baseflow happened in March 2018 (1.37%) as estimated by sliding interval method. This peak is proved by the apparent increase of Kimani River flow during the wet seasons.

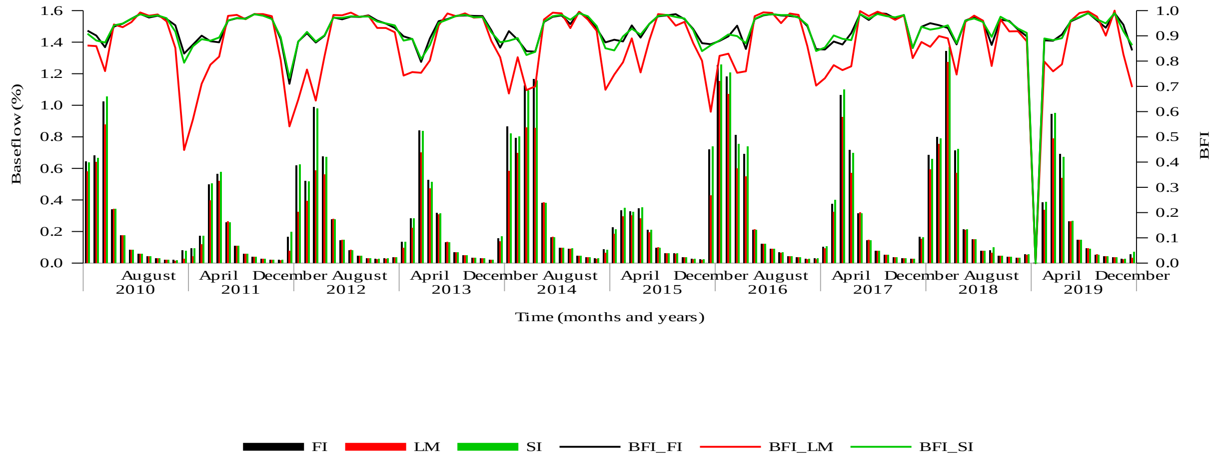

Figure 3.6: Baseflow separation techniques along with BFI for Kimani at GNR

3.4.1.5 Mbarali at Igawa

The relationship between groundwater discharge and river flow occurred during the whole period ranging from 2010 to 2019. Through wet and dry season, the baseflow contributions to the river are evident. Likewise, the baseflow indices increased in dry seasons and decreased in wet seasons as it appears in Figure 3.7, indicating the contribution of baseflow to the river flow. Among all the techniques, the sliding interval method appears to have the highest baseflow indices in wet seasons while being almost the same as for the fixed interval method during the dry seasons.

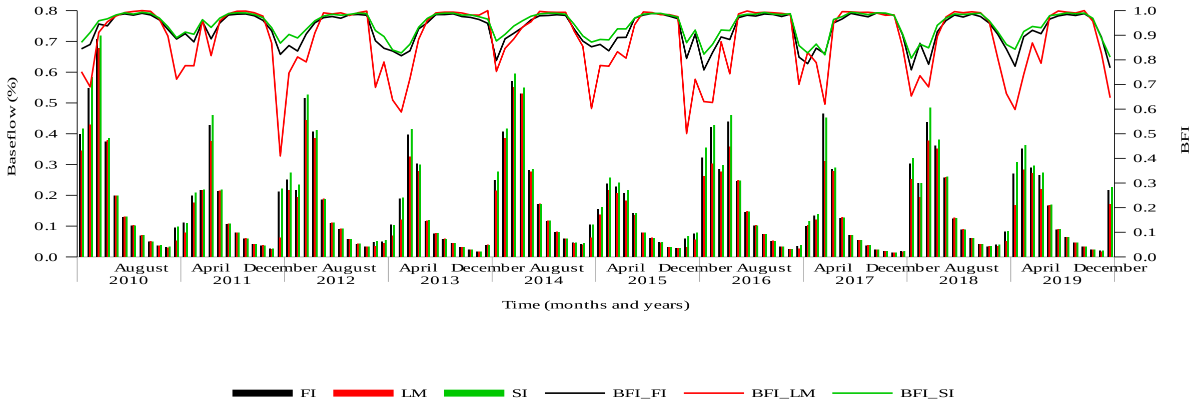

Figure 3.7: Baseflow separation techniques along with BFI for Mbarali river at Igawa

3.4.1.6 Ndembera at Ilongo

The groundwater discharge and Ndembera river flow interactions at Ilongo gauging station are remarkable all along the period and in all the seasons. In April 2014, the sliding interval method registered a high baseflow value (0.8%). But as it can be seen in Figure 3.8, there were significant decrease of baseflow during dry seasons, hence the low river discharges. Apart from 2014, groundwater discharges remained below 0.5% in wet seasons and less than 0.05% in dry seasons throughout the time range (Figure 3.8).

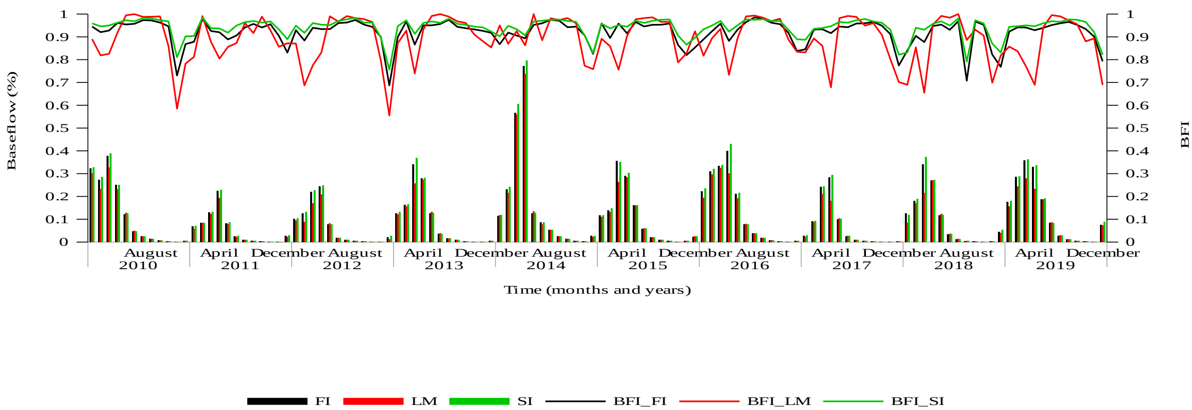

Figure 3.8: Baseflow separation techniques along with BFI for Ndembera at Ilongo

3.4.2 Assessment of temporal relationship between baseflow index and river flow

Table 3.6 shows the mean annual and seasonal (wet and dry) baseflow indices derived from the three hydrograph separation techniques used in this study for the six river gauging stations. The GRR at Msembe station registered the BFIs varying from 68% to 80% for the three techniques with the period ranging from 2010 to 2019. For the five remaining rivers (Chimala, GRR at Salimwani, Kimani, Mbarali and Ndembera), this study found the baseflow indices' contribution fluctuating from 80% to 98% as it appears in Table 3.6. As the Sliding Interval was found the method with high baseflow indices, it is considered in the BFI-River flow temporal relationship assessment and in the baseflow trends analysis. On the annual basis, Chimala river discharges are made of 96% of groundwater discharges, GRR at Msembe receives 75% of baseflow, GRR at Salimwani gets 95% of baseflow. Kimani river is recharged by 92% from groundwater discharges while Mbarali and Ndembera are having 94% of baseflow. Seasonally, the groundwater discharges to river flows decreases during the wet season compared to the increase of baseflow registered in the dry season. This does not apply to the GRR at Msembe, where the baseflow augmented trough the wet season (77%) but declined in the dry seasons (71%). The decrease of groundwater discharges to rivers in the wet season is obviously occasioned by the surface runoff and rainfall contributions to rivers.

Table 3.6: Mean annual and seasonal baseflow indices for the six-river gauging stations

River	Period	FI	LM	SI
Chimala	Annual	0.96	0.94	0.96
	Wet	0.95	0.92	0.95
	Dry	0.98	0.97	0.98
Msembe	Annual	0.73	0.74	0.75
	Wet	0.76	0.68	0.77
	Dry	0.70	0.81	0.71
Salimwani	Annual	0.93	0.89	0.95
	Wet	0.90	0.83	0.92
	Dry	0.97	0.97	0.98
Kimani	Annual	0.92	0.87	0.92
	Wet	0.89	0.81	0.89
	Dry	0.96	0.94	0.96
Mbarali	Annual	0.93	0.88	0.94
	Wet	0.90	0.83	0.92
	Dry	0.96	0.96	0.97
Ndembera	Annual	0.92	0.89	0.94
	Wet	0.91	0.87	0.93
	Dry	0.93	0.92	0.95

3.4.3 Temporal BFI trend analysis

The Mann-Kendall (MK) test was used to analyze the statistically significant trends of the BFI of the six river gauging stations. The findings are illustrated in Table 3.7 where Z is the test statistic of MK test, T standing for trend category and -1 meaning non-significant decreasing trend, +1 signifies non-significant increasing trend and 0 indicates no trend at all (Table 3.7). In general, for all rivers’ catchments, there are non-significant baseflow trends either increasing (+1) or decreasing (-1) according to the results of the MK test. This specifies that, though statistically non-significant, the groundwater discharges to rivers in the Usangu Plains is not stable.

For Chimala and Mbarali rivers, this study found the baseflow unhurriedly declining during all seasons. The groundwater discharges to GRR at Salimwani slowly increase annually, in dry and wet seasons. A non-significant baseflow increase is visible annually and in dry season to the GRR at Msembe while it decreases in wet season. The baseflow contribution to Kimani River tends to increase in the annual and wet season, though it decreases in dry season. Centrally, the groundwater discharges to Ndembera river tends to decrease in annual and wet season while it increases in dry season. Even though the baseflow trends are non-significant, the increasing trend shows the cumulative variation of groundwater discharges to rivers while the opposite applies to the decreasing baseflow trend.

Table 3.7: Results of MK statistical test for the BFI of six river gauging stations

River	Period	FI		LM		SI	
		Z	T	Z	T	Z	T
Chimala	Annual	-0.38	-1	-0.07	-1	-0.38	-1
	Wet	-0.24	-1	0.07	+1	-0.38	-1
	Dry	-0.24	-1	-0.38	-1	-0.32	-1
Msembe	Annual	0.11	+1	0.07	+1	0.07	+1
	Wet	-0.07	-1	0.07	+1	-0.11	-1
	Dry	0.29	+1	0.29	+1	0.25	+1
Salimwani	Annual	0.16	+1	0.07	+1	0.07	+1
	Wet	0.11	+1	0.02	+1	0.07	+1
	Dry	0.38	+1	0.33	+1	0.38	+1
Kimani	Annual	-0.02	-1	0.24	+1	0.02	+1
	Wet	0.16	+1	0.24	+1	0.16	+1
	Dry	-0.38	-1	-0.38	-1	-0.16	-1
Mbarali	Annual	-0.69	-1	-0.29	-1	-0.87	-1
	Wet	-0.73	-1	-0.29	-1	-0.69	-1
	Dry	-0.02	-1	-0.07	-1	-0.16	-1
Ndembera	Annual	-0.07	-1	-0.24	-1	-0.11	-1
	Wet	-0.29	-1	-0.29	-1	-0.38	-1
	Dry	0.11	+1	0.02	+1	0.11	+1

3.4.4 Comparison of rainfall against river discharges of all gauging stations

The interaction between river discharges and rainfall in the wet and dry seasons is illustrated in Figure 3.9. As for Chimala at Chitekelo, Kimani at GNR and GRR at Salimwani, the discharges exceeded the amount of rainfall from May to September. This implies the interaction between the two rivers and the groundwater in their respective catchments. However, the GRR at Msembe seemed highly dependent on rainfall for the discharges variate accordingly in wet and dry seasons.

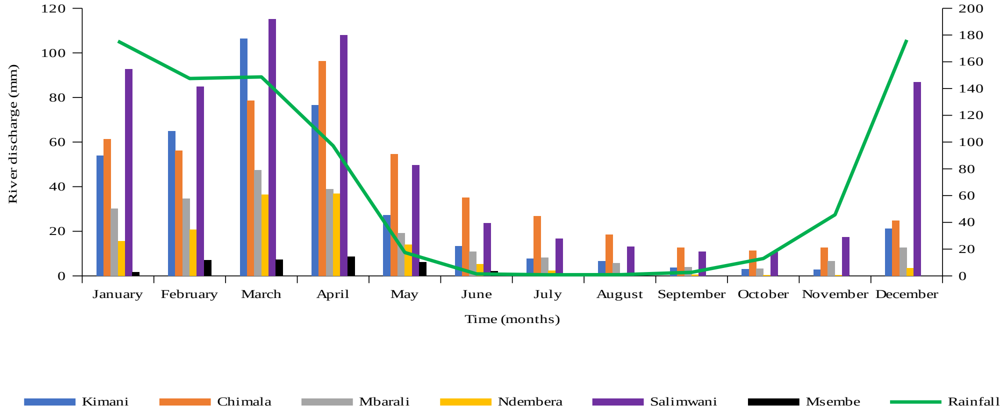

Figure 3.9: Mean-monthly relationship of rainfall and river discharges for 2010-2019

3.5 Discussion

The aim of this study was to estimate the interaction between groundwater and surface water at six different river gauging stations of six different rivers. The quantification of the interconnectedness between rivers and groundwater is of great importance for the watershed management and water resources sound planning (Ahiablame *et al.*, 2017). This study used three different baseflow separation methods to separate groundwater discharges from river flows. All baseflow separation techniques indicated that the groundwater-surface water interaction exists and the baseflow contribute substantially to the sustainable river flows in the Usangu Plains during both dry and wet seasons, but especially in dry seasons (Figures 3.2 - 3.8). The results of this study agreed with the findings of Benedict (2019) who reported the decreases of Ndembera river discharges due to changes in land use/land cover in the catchment and water withdrawal to irrigate onions and rice along the river. At Ilongo gauging station of Ndembera river, about 43% of the time range have flow values below 1 m^3/s in dry season.

Particularly, GRR at Msembe dried up in all the years of the period for several days except for 2014 and 2015 (Table 3.5). There were about 128 days throughout the time range (2010 - 2019) where discharges of GRR at Msembe fluctuated between 0.001 and 1.00 m^3/s. These results were in agreement with those reported by Kashaigili *et al.* (2006) indicating that GRR dried up for some days from 1994 to 2004. This decline of GRR flow at Msembe can be subjected to anthropogenic activities mainly irrigated agriculture happening in the catchment as narrated by Kashaigili *et al.* (2006). GRR at Salimwani, Chimala river, Kimani River and Mbarali river showed high values of flows in wet seasons but declined not significantly in dry seasons. The sliding interval method was found to have high baseflow indices (Table 3.7) compared to fixed interval and local minimum methods similarly to the results reported by Mohammadlou and Zeinivand (2019) and Helena (2016).

Considering the Sliding Interval method, the baseflow indices were found varying between 89% and 98% for other rivers except GRR at Msembe where the indices are 71%, 75% and 77% for dry, wet and annual seasons, respectively (Table 3.7). The findings of this study for GRR at Msembe differ from the results of Kashaigili *et al.* (2006) showing that 89% of the annual (1958-1973) river discharge are from the baseflow using the Desktop Reserve Model. The groundwater discharges to rivers (Chimala, Ndembera, Mbarali, Kimani and GRR at Salimwani) appeared very high in the dry season (Table 3.7) and low in wet season due the seasonal variations of rainfall (Figure 3.9) and surface runoff. The decline of baseflow to GRR at Msembe during dry season confirmed the literature stating that groundwater abstractions for irrigation, domestic use, brick-making are the major causes of low baseflow (Benedict, 2019; Kashaigili *et al.*, 2006). This study revealed that the rivers located in the highlands are more dependent on groundwater discharges than the GRR at Msembe which is in the lowlands (Table 3.1 and Figure 3.1). This is similar to the fact that the highlands are considered as recharge zones while lowlands are discharge zones (SMUWC, 2001).

The statistical results of the Mann-Kendal test for the baseflow indices of the river flows are similar to the observed flows in the GRR at Msembe which indicated a non-significant trend in the annual flows (Kashaigili *et al.*, 2006). According to Kelly *et al.* (2019), lack of increasing or decreasing trend suggests that the groundwater discharges to rivers are stable and that the catchment might be enduring minimal human impacts. However, this study found that during annual, wet and dry seasons there are increasing and decreasing trends in the baseflow though they are statistically non-significant. Increasing trends indicate a rising in groundwater table and are due to the increase in good land conservation, land cover, forestation, high amount of rainfall and of course less surface runoff while the opposite produces the decreasing trends in baseflow (Ahiablame *et al.*, 2017; Benedict, 2019).

3.6 Conclusions and Recommendations

In conclusion, this Study used three different hydrograph separation techniques to estimate the contribution of groundwater discharges to the river flow at six different locations within the Usangu Plains. GRR at Msembe showed no flows during a number of days and this aligned with the literature where human activities such as irrigated agriculture, domestic water-requiring events, livestock, and many more were pointed to be the driving forces of the observed declines of river discharges. The comprehensive understanding of groundwater discharges to rivers in the Usangu Plains is of immense capital in the management and utilization of the water resources. Except GRR at Msembe, the other five rivers manifested a great reliance on the baseflow with more than

90% of it in the river flows. This calls for the need of studies on how to conjunctively use the surface and groundwater in the Usangu Plains for enhancing the welfare of the water users.

Land and water management strategies such as water allocation measures, sound water usage practices, and afforestation may be better approaches to counteract the declines of water flows in rivers of the Usangu Plains, specifically in the dry season. Moreover, placement of observation wells close to the river gauging stations could benefit in evaluating the seasonal variability of groundwater discharges to rivers. Also, future studies should use the methods which consider the evapotranspiration, hydraulic heads, and groundwater abstraction information to quantify the groundwater-surface water interaction in the Usangu plains.

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CHAPTER FOUR

4.0 Evaluation of the future climate change influence on the groundwater recharge in the Usangu Plains, Tanzania

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4.1 Abstract

In the Usangu Plains, groundwater is of great help as it sustains surface water and supports the domestic use and crop water requirements during climate changing phenomena. However, the future climate is projected to greatly change, and its variations will through various means affect the groundwater recharge dynamics. Here we used the WetSpass model to simulate the future temporal and spatial variations caused by climate (precipitation, temperature, wind speed and evapotranspiration) change in the future water budget components. The Coefficient of variation was calculated for each component to examine its variations. The results indicated that, through two scenarios (RCP-45 and RCP-85), surface runoff and actual evapotranspiration will be increasing while the groundwater recharge magnitude and distributions will decrease. The recharge zone with high rates is projected to reduce to less than 5% of the whole Usangu catchment compared to 15% found in the second chapter. This decrease will affect rivers in the catchment and cause considerable declines, hence low water availability to meet the crop, domestic use, and economic water requirements. Therefore, the application of rainwater harvesting technologies and managed groundwater recharge approaches will enhance the water availability for ecosystems, domestic and economic use in the Usangu Plains.

Key words: Climate Change, Groundwater recharge, WetSpass model

4.2 Introduction

Significant influences of climate change and human disturbances on water resources, environmental ecosystems and agricultural productivity are obviously noticeable in all parts of the world and tend to increase (Haddeland *et al.*, 2014). The mitigation or adaptation to these global changes in climate and the associated consequences require serious ahead-plans and informed communities. Historical climate variability has been impacting the hydrologic cycle and all the accompanying anthropogenic activities all over the world (Shemsanga *et al.*, 2010), though little care has been taken. Temporal and spatial changes in precipitation and temperature play a tremendous role in surface water sustainability, groundwater recharge processes and groundwater-surface water interactions (Kumar *et al.*, 2017). To that, groundwater resource has a very huge contribution in the wellbeing of the communities especially agriculture-dependent societies in arid and semi-arid regions (Siebert *et al.*, 2010). Generally, the current world population (7.7 billion in 2019) is projected to highly increase (11.2 billion) by the end of the 21st century (UN, 2007), hence the rise in water and food demand worldwide. The humankind is greatly accused to cause rapid climate change and global warming through industrialization, emissions of greenhouse gases and urbanization (Agrawala *et al.*, 2003). Consequently, future climate changes are worthy a substantial consideration to ensure the protection and sustainability of groundwater resources.

Largely, the linkage between climate change and groundwater resources is meant to happen indirectly through its interrelation with surface water resources (Kishiwa *et al.*, 2018). But, directly, the changes of climate variables such as temperature and precipitation influence the temporal and spatial distribution and magnitude of groundwater recharge worldwide (Zhou *et al.*, 2011). In Africa, the visible negative outcomes of climate change are showcased by droughts, floods, high groundwater abstractions and many more (IPCC, 2014). Still, Africa is said to be the most vulnerable continent of future climate change on this planet due to its high exposure and low adaptive capacities (IPCC, 2019). In Sub-Saharan Africa, farmers whose sole source of income is agriculture, are heavily affected by climate change (URT, 2015).

In Tanzania, the documented climate change effects affecting small scale farmers are higher rainfall variability, reduced water volumes in water bodies, change in cropping seasons, replacement of crop varieties (WB, 2017), to mention but a few. Yet, future climate change projections, though uncertain, predicted high rainfall variability with reliability to reduce, hence droughts and/or floods are expected to be consistent and severe (WB, 2017). This calls for abrupt shifts of water withdrawal towards groundwater for agriculture, domestic use, livestock, industrialization, and hydropower. However, there had been very little research on the possible effects of future climate change on groundwater resources in Tanzania.

Usangu Plains, located in the southern highlands of Tanzania, have been of great benefits in improving the livelihood of smallholder farmers through irrigated as well as rainfed agriculture and other water-based activities (Kadigi *et al.*, 2004). Still, agricultural sector is considered as the major water user in the Usangu relying on both groundwater and surface water resources (Kashaigili *et al.*, 2006). Unfortunately, the current climate variability is projected to negatively increase and continue impacting small scale farmers given their unawareness and reduced adaptive measures (URT, 2014). Conversely, few studies in Usangu Plains inform about the impacts of future climate change on the major hydrological cycle components such as actual evapotranspiration, surface runoff and groundwater (Benedict, 2019). Data paucity and uncertainty in climate projections are the causes of knowledge gaps on how the future climate variability will affect the spatial and temporal groundwater recharge magnitude and distributions in the Usangu plains (URT, 2014). Therefore, there is an urgent and unavoidable need of understanding on future climate change impacts towards groundwater recharge for enriching the management and future measures of adaptation and/or mitigation with the Usangu Plains.

Future projections of climate variables are sourced from global and regional climate models (GCMs and RCMs) which considered different scenarios of future anthropogenic and natural forcing factors (Benedict, 2019). In the western part of Tanzania, temperature is expected to rise (+1.9ºC) and precipitation is projected to increase (+1%) by 2050 (Rowhani *et al.,* 2011). Besides, the Coordinated Regional Downscaling Experiment (CORDEX)-Africa framework, supported by the World Climate Research Program (WCRP) and assessed by the Intergovernmental Panel on Climate Change (IPCC), is recommended to provide regionally downscaled future climate variables at a spatial resolution of 0.44º x 0.44º (50km x 50km) (Mutayoba and Kashaigili, 2017). To simulate hydrologic effects of future climate change, various approaches have been applied worldwide, however, numerical modelling is advised to generate rapid and accurate results for water budget components (Jyrkama and Sykes, 2016). Correspondingly, the geographical information system (GIS)-based hydrological model named Water for Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State (WetSpass) was used to evaluate the future temporal variations and spatial differences of groundwater recharge in the Usangu Plains.

This study tried to bridge the gaps by evaluating the influence of future climate change on groundwater recharge in the Usangu Plains. Its specific objectives were to (a) assess the spatial and temporal variations of future water balance components and (b) examine future groundwater recharge potential areas in order to generate the basic understanding for the future sustainability of groundwater resources and improvement of the agricultural outputs.

4.3 Materials and Methods

4.3.1 Description of the study area

The study was conducted in Usangu plains, Tanzania (Figure 4.1). The area is located at an average elevation of 1100 m above mean sea level (amsl). The area is encircled by the Kipengere, Poroto and Chunya mountains with an elevation reaching 3000m amsl. Usangu Plains cover an area of approximately 20 810 km^2 (Kadigi *et al.*, 2004) and lie between latitudes 7^{o}41’ and 9^{o}25’ South and longitudes 33^{o}40’ and 35^{o}40’ East. Its climate is mostly influenced by the air mass movements together with inter-tropical convergence zone (Kashaigili *et al.*, 2006). The Usangu Plains’ rainfall regime is unimodal, having one wet season from December to June, with some irregularities, the rainfall distribution varies spatially and is very localized depending on the altitude (Kashaigili *et al.*, 2006). The mean annual rainfall is between 1000 and 1600 mm within the highlands while the central plains, formed of dry fans and wetlands ecosystems, receives 500-700 mm from July to November (Malley *et al.*, 2009).

The Usangu Plains’ mean annual temperature is between 18^{o}C and 28^{o}C in the highlands and lower parts, respectively and its mean annual potential evapotranspiration goes up to 1900mm (SMUWC, 2001). The land vegetation cover differs from the high to the low altitudes, where between 2000m and 1100m amsl are dominated by the miombo woodland and below 1100m amsl are the fans, the wetland ecosystems, and agricultural lands (SMUWC, 2001). The high increase of population and the expansion of anthropogenic activities within and in the vicinity of the wetlands have caused the extreme water demand. In both dry and wet seasons, there are water demand for irrigation, domestic use, livestock, brickmaking, and hydropower which is the major water user though taking place a long way downstream (SMUWC, 2001).

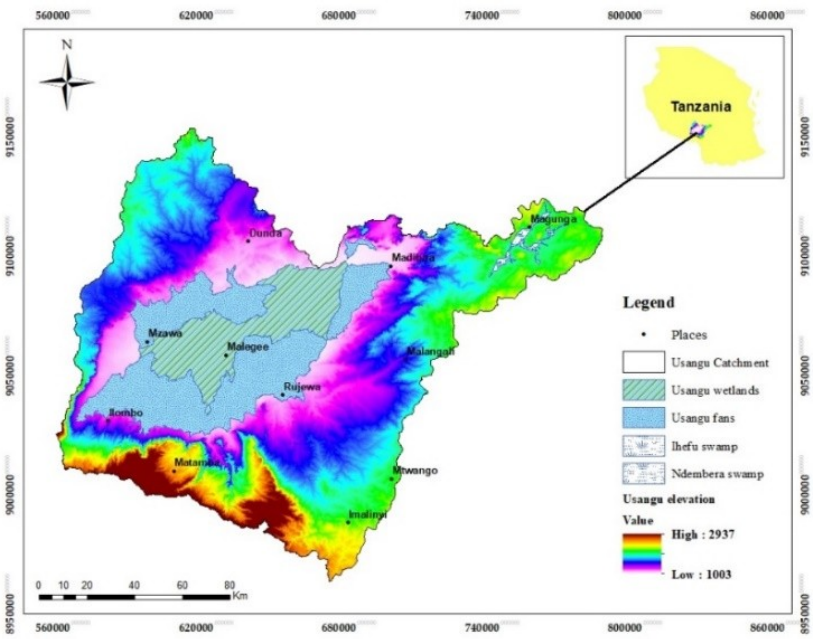


Figure 4.1: Map of Usangu Plains showing topography, fans, wetlands, and swamp

4.3.2 Description of the WetSpass model

The WetSpass model is used to evaluate the influence of future climate change on groundwater recharge in the Usangu Plains. The model is meant to simulate the temporal average and spatial differences of groundwater recharge, surface runoff and actual evapotranspiration.

WetSpass stands for Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State (Batelaan and De Smedt, 2001). This model is fully integrated in the GIS ArcView (version 3.2) as raster model, coded in Avenue. WetSpass is a steady state spatially distributed and physically based water balance model. It simulates yearly and seasonal long-term average spatial patterns of the water budget components by employing physical and empirical relationships. Inputs for this model include grids of land use, groundwater depth, precipitation, potential evapotranspiration, wind-speed, temperature, soil and slope whereby parameters such as land-use and soil types are connected to the model as attribute tables of their respective grids.

Given that WetSpass is a distributed model, the water balance calculation is executed at a raster cell level. Individual raster water balance is obtained by summing up independent water balances for the vegetated, bare soil, open water, and impervious fraction of a raster cell (Figure 4.2). The total water balance of a given area is thus calculated as the summation of the water balance of each raster cell (Batelaan and De Smedt, 2007). Concerning a vegetated area, the water balance depends on the average seasonal precipitation (P), interception fraction (I), surface runoff (S_v), actual transpiration (T_v) and groundwater recharge (R_v) all with the unit of [LT^{-1}]. Due to the absence of vegetation in the bare soil, open water, and impervious fraction cells, the ET_v becomes E_s for there is no transpiration and interception components. Referring to the equations given below:

$P = I + S_v + T_v + R_v$……………………….…………………………..........………..(1)

Firstly, the interception (I) portion represents a constant percentage of the annual rainfall value, depending on the type of the vegetation. Hence, the fraction declines with an increase in an annual total precipitation amount.

Secondly, the computation of the surface runoff is related to the amount of precipitation, its intensity, interception and soil infiltration. The surface runoff is calculated in two steps:

a) Initially, the potential surface runoff ($S_{v\text{-}pot}$) is calculated as follow:

$S_{v\text{-}pot} = C_{sv}(P\text{-}I)$……………...……………..…………………………………….. (2)

Where, C_{sv} is a surface runoff coefficient for vegetated infiltration areas, and is a function of vegetation, soil type and slope. P is the average seasonal precipitation [LT^{-1}] and I is the interception fraction [LT^{-1}].

In the second step, the actual surface runoff is calculated from the $S_{v\text{-}pot}$ by considering the differences in precipitation intensities related to the soil infiltration capacities.

$Sv = C_{HOR}Sv\text{-}pot$…………………………….………..…………………………(3)

Where C_{HOR} is a coefficient for parameterizing that part of a seasonal precipitation contributing to the Hortonian overland flow.

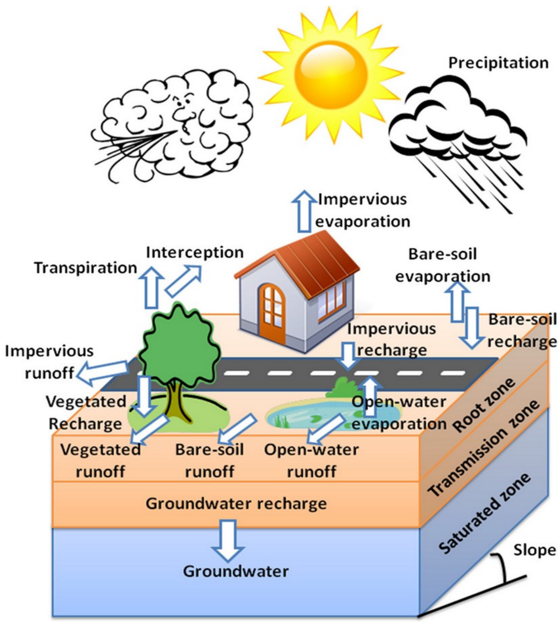


Figure: 4.2: Schematic representation of water balance for a hypothetical landcover grid cell (Batelaan and De Smedt, 2007)

To calculate a seasonal evapotranspiration, a transpiration reference value is obtained from open water evaporation and a vegetation coefficient:

$T_{rv} = cE_o$ ……………………………………………………………………………. (4)

Where T_{rv} is the reference transpiration of a vegetated surface [LT^{-1}], E_o the potential evaporation of open water [LT^{-1}] and c the vegetation coefficient [dimensionless].

This vegetation coefficient (c) can be calculated as the ratio of reference vegetation transpiration to the potential open-water evaporation as given by the Penman-Monteith equation:

$$C = \frac{1 + \frac{\gamma}{\Delta}}{1 + \frac{\gamma}{\Delta}\left(1 + \frac{r_c}{r_a}\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where: γ = psychrometric constant $[ML^{-1}T^{-2}C^{-1}]$,

Δ = slope of the first derivative of the saturated vapor pressure curve (slope of saturation vapor pressure at the prevailing air temperature) $[ML^{-1}T^{-2}C^{-1}]$,

r_c = canopy resistance $[TL^{-1}]$ and

r_a = aerodynamic resistance $[TL^{-1}]$ given by

$$r_a = \frac{1}{k^2 \; U_a}\left(\ln\left(\frac{Z_a - d}{Z_0}\right)\right)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Where: K is the Von Karman constant (0.4) [dimensionless],

U_a is the wind speed $[LT^{-1}]$ at measurement level Za (height above the ground) = 2m,

d is the zero-plane displacement length [L] and

Z_o is the roughness length for the vegetation or soil [L].

Lastly, the groundwater recharge for vegetated area is then calculated as a residual term of the water balance taking into account the above three components,

$$R = P - S_v - ET_v - I \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

R is the groundwater recharge, P is the precipitation, S_v the surface runoff, ET_v is the actual evapotranspiration and I the interception fraction, all with the unit $[LT^{-1}]$. The same process as that of the computation for the vegetated area is followed to calculate the water balance for bare soil, impervious areas, and open water. Due to the absence of vegetation in these places, the ET_v becomes E_s for there is no transpiration and interception components. Using the water balance components of vegetated, bare soil, open water and impervious areas, the total water balance of a raster cell is therefore calculated as illustrated in the below equations:

$$ET = a_v ET_v + a_s E_s + a_o E_o + a_i E_i \quad (8)$$

$$S = a_v S_v + a_s S_s + a_o S_o + a_i S_i \quad (9)$$

$$R = a_v R_v + a_s R_s + a_o R_o + a_i R_i \quad (10)$$

Where ET, S and R are the total evapotranspiration, surface runoff, and groundwater recharge of a raster cell respectively, each having a vegetated, bare soil, open water and impervious area component denoted by a_v, a_s, a_o, and a_i, respectively.

4.3.3 Description of input data for WetSpass model

As per the WetSpass model requires seasonal-based parameters, seven months (December, January, February, March, April, May, and June) are considered as wet (winter) season and the remaining five months (from July to November) as dry (summer) season for the case of Usangu Plains (Kashaigili *et al.*, 2006). The inputs data were prepared in the form of grid maps using ArcGIS software version 10.8 and parameter tables were edited in Microsoft Excel 365 and converted to dbf format by Advanced XLS Converter. The grid maps were of land-use/land cover, wind speed, soil texture, slope, topography, potential evapotranspiration, temperature, groundwater levels, and precipitation. The cell size of grid maps was 30m by 30m and had 7646 columns and 6345 rows. The grid maps were prepared through the ArcGIS environment using Inverse Distance Weigh (IDW) interpolation method. The nearest and bilinear resampling techniques were used to set, respectively, continuous (all weather parameters) and discrete (soil) grid maps to the same resolution (30m). The input files prepared as parameter tables were dry and wet land use/land cover, soil texture and runoff coefficient. The runoff parameter table contains runoff coefficients for land use, soil type and slope angles.

4.3.3.1 Hydrometeorological inputs

Future simulated data of precipitation, maximum and minimum temperature, wind speed, relative humidity and solar radiation from the Coordinated Regional Downscaled Experiment (CORDEX-Africa) were used in this study. The monthly climatologic data for 30 years (2021-2050) with the spatial resolution of 0.44º by 0.44º (approximately 50 km by 50 km) were obtained from the Rossby Center Regional Atmospheric Climate model (RCA4) managed by the Swedish Meteorological and Hydrological Institute (SMHI) of Sweden [*https://esgf-data.dkrz.de/search/cordex-dkrz/*; site visited on 06/05/2021] because of its minimum absolute biases compared to other RCMs.

The simulated data generated by the RCA4 model are driven by the Centre National de Recherches Météorologiques-Centre Européen de Recherche et Formation Avancée en Calcul Scientifique (CNRM-CERFACS-CNRM-CM5) Global Climate Model (GCM). In this study, only two Representative Concentration Pathways (RCP) based on radiative forcing degrees of 4.5 and 8.5 W/m^2 corresponding to RCP4.5 and RCP8.5 (Vuuren *et al.*, 2011) were considered. The RCP4.5 scenario is the intermediate pathway around the stabilization level supposing that mitigation measures are taken into account worldwide (Thomson *et al.*, 2011). The RCP8.5, the worst scenario case, represents the highest RCP scenario regarding greenhouse gas emissions without explicit mitigative or adaptative climatic strategies and policies (Riahi *et al*., 2011). The data were in a Network Common Data Format (NetCDF) and were converted into Comma Separated Values (CSV) format using the R programming software. The actual evapotranspiration was computed through the Instat computer package which uses the FAO-Penman Monteith equation, as it is globally recommended for calculating the evapotranspiration

(Rwebugisa, 2008). For the WetSpass demands meteorological inputs in the grid format on a seasonal basis, the IDW interpolation method in the ArcGIS environment was used to prepare the grid maps of precipitation, temperature, wind speed and evapotranspiration; both for wet and dry seasons.

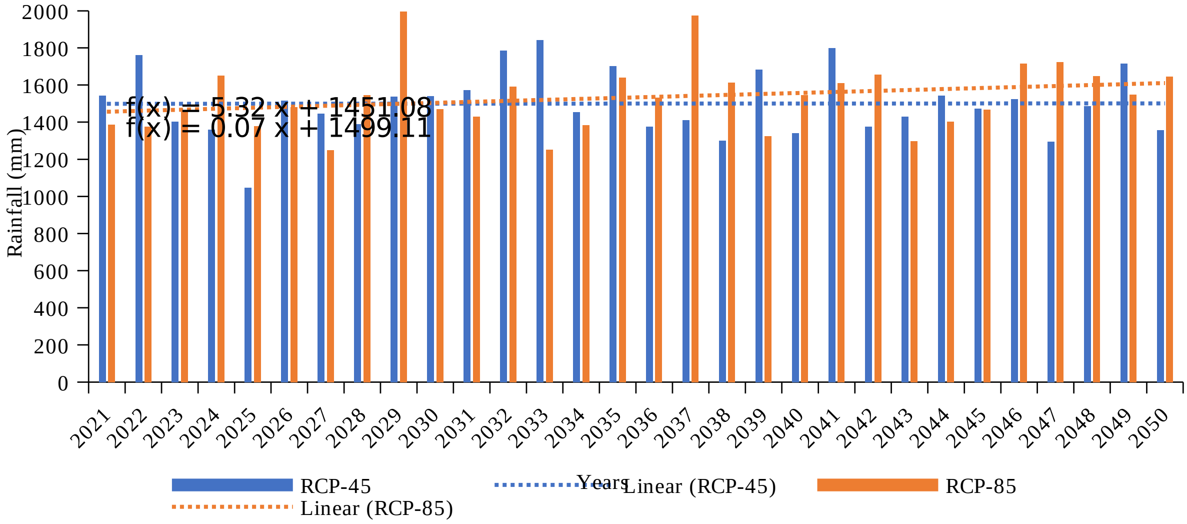


Figure 4.3: Projected mean annual rainfall data

Table 4.1: The summary of projected meteorological data (source: own processing)

	Scenario	**RCP-4.5**			**RCP-8.5**		
Parameter	**Season**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**
Precipitation (mm)	Wet	181	3246	1137	189	3249	1144
	Dry	64	1113	363	71	1200	390
	Annual	245	4200	1500	260	4280	1534
Temperature (C)	Wet	17.5	22	19.6	17.7	22.1	19.8
	Dry	17.2	21.7	19.4	17.4	21.9	19.7
	Annual	17.4	21.9	19.5	17.6	22	19.7
Wind speed (m/s)	Wet	2.5	3.1	2.8	2.5	3.1	2.8
	Dry	3.3	4.2	3.8	3.3	4.2	3.8
	Annual	3.0	3.7	3.3	3.0	3.7	3.3

Evapotranspiration (mm)	Wet	1107	1381	1218	1115	1386	1225
	Dry	862	1091	976	868	1096	981
	Annual	1974	2472	2195	1988	2482	2206

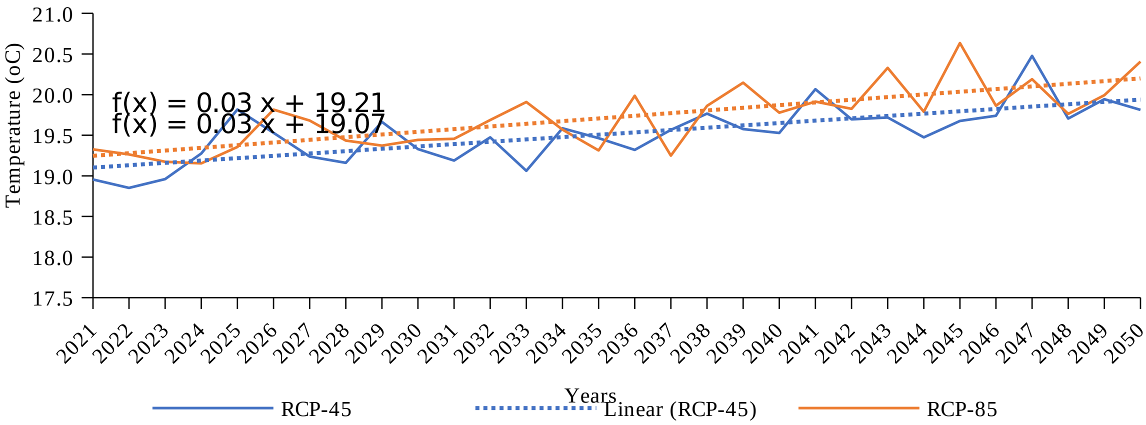


Figure 4.4: Projected mean annual temperature

Historical (2015-2020) daily groundwater (GW) data from the Rufiji Basin Water Board (RBWB) were used for the simulation. The IDW interpolation technique of the ArcGIS environment was used to generate the grid maps of wet and dry seasons of GW depths. The adoption of mean GW depths does not influence the WetSpass simulation results if the GW depths in the study area are more than the root depths (Tilahun and Merkel, 2009).

4.3.3.2 Areal-based biophysical inputs

i. Topography and slope

For slope and topography data, digital elevation model (DEM) of the study area was extracted from the Shuttle Radar Topography Mission (SRTM) available on the United States Geological Survey (USGS) earth explorer website [https://earthexplorer.usgs.gov/, site visited on 19/03/2021] at a spatial resolution of 30m. The raster images were imported into ArcGIS 10.8 and merged to cover the whole study area. With the

Usangu basin boundary, its raster was clipped from the combined satellite images. The clipped raster of Usangu was used to create elevation and slope grid maps of the Usangu Plains using spatial analyst tools of ArcGIS 10.8, considering the year 2017 for spatial data. The elevation ranges from 1003m to 2956m above mean sea level with an average of 1429m and the slope varies from 0% to 74%.

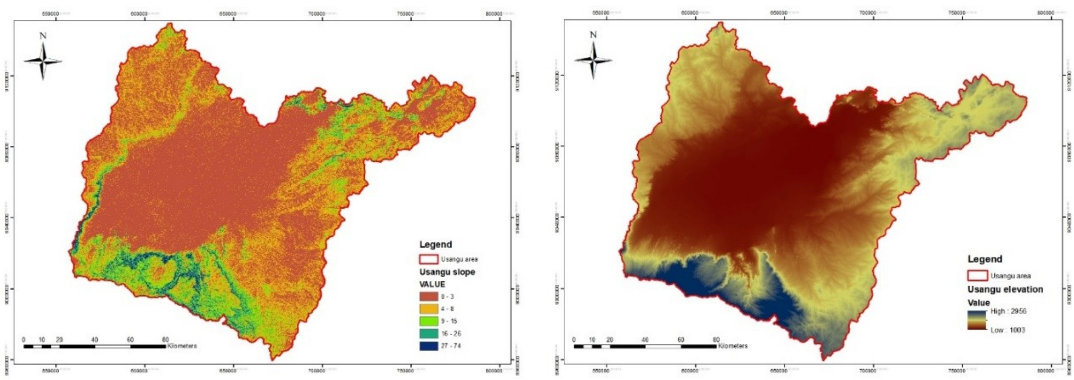


Figure 4.5: Slope map (left) and topographic map (right) of Usangu Plains

ii. Soil texture

Soil textural information is an important input of the WetSpass model for the recharge quantification. As far as this study is concerned, the soil data were obtained from the FAO-UNESCO [*http://www.fao.org/geonetwork/srv/en/metadata.show%3Fid=14116*; site visited on 24/03/2021] digitized (vector dataset) soil map of the world at a scale of 1:5 000 000. ArcGIS software was used to clip the soil textural map of the Usangu Plains from the digital soil map of the world. The attribute table of soil textures of Usangu was adjusted using the Soil Water Characteristics program developed by United States Department of Agriculture (USDA) Agricultural Research Service [*http://hydrolab.arsusda.gov/soilwater/Index.htm*; site visited on 29/03/2021]. The textural classes were found to be clay (24%), clay loam (32%), sandy clay loam (13%), loamy sandy (3%) and sandy loam (28%). The soil classes outputs of this program were validated based on the soil textural triangle.

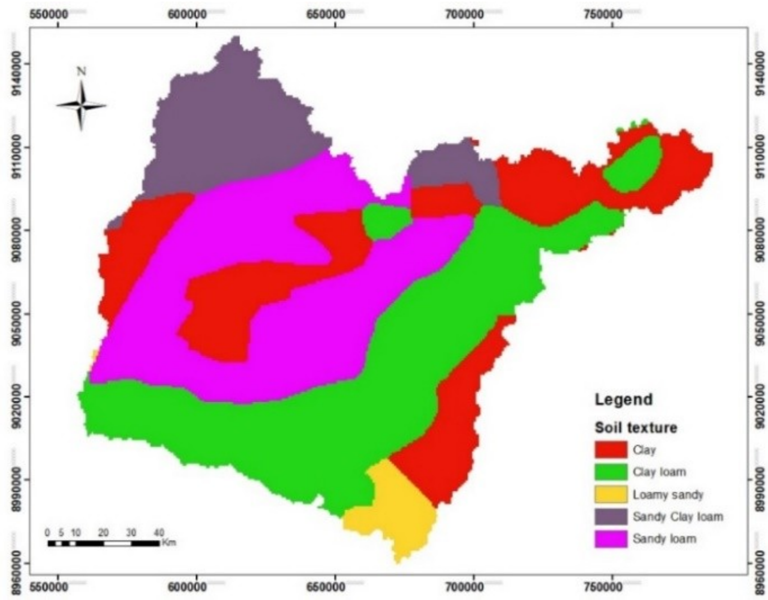


Figure 4.6: Soil textural map of the Usangu plains

iii. LULC classification

Land use/land cover data were processed based on Landsat 8 images of the year 2017 extracted from the USGS earth explorer website at a spatial resolution of 30m. Usangu catchment covers three different paths and rows, the periods of the Landsat images used in the area of interest and their respective rows and paths are given in Table 4.2. Land use classification was made using Random Forest classifier in the R-Studio software after performing a supervised classification in ArcGIS environment to generate the spectral classes (regions of interest, ROI). The classification accuracy assessment was executed based on the Google Earth pro truths of the Usangu catchment boundaries. The overall classification accuracy was 82.5% while the overall Kappa statistics was 83.2%. Normally, the land use/ land cover classification accuracy assessment results in this study are satisfactory, for the kappa statistics greater than 80% represent strong accuracy between the performed classification and ground truth information (Manandhar *et al.*, 2009).

Table 4.2: Characteristics of the Landsat 8 images of the Usangu Plains

Period	Path	Row
2017-05-02 / 2017-05-15	168	066
2017-11-17 / 2017-11-22	169	066
2017-11-17 / 2017-11-22	169	065

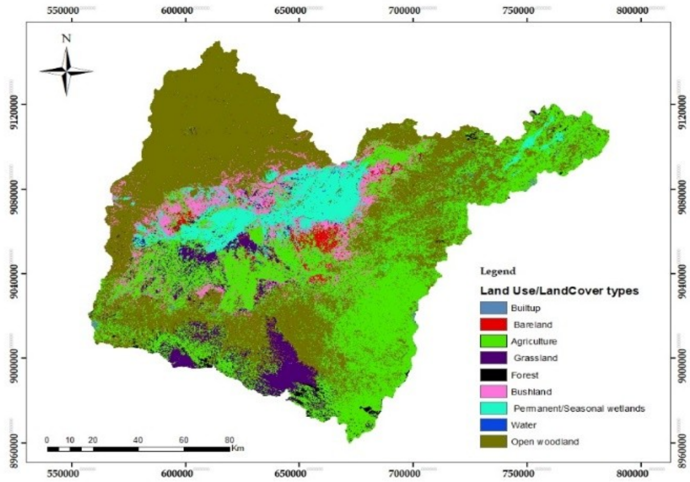


Figure 4.7: LULC maps of the Usangu Plains

4.4 Results

4.4.1 Projected distribution of water balance components of the Usangu Plains

4.4.1.1 Surface runoff

The projected mean annual surface runoff (SR) simulated by the WetSpass is shown in Figure 4.8. The model estimated that the surface runoff, in the next 30 years (2021-2050), will be varying from 0 to 2609mm in RCP-45 scenario and from 0 to 2614mm in RCP-85 with averages of 227mm and 234mm, respectively. During the RCP-45 scenario, about 15% of the mean annual rainfall (1500mm) will be lost through surface runoff, that is (i.e), 66% (150mm) of mean annual surface runoff in the wet surface runoff occuring in the wet season and 34% (77mm) in the dry one. For the RCP-85, also about 15% are projected from the rainfall but with 65% (152mm) in the wet season and 35% (82mm) in the dry season (Table 4.3).

The high surface runoff is projected to occur in the built-up and bareland land cover types in RCP-45 scenario and built-up and agriculture in RCP-85. For the soil types, the surface runoff is expected to be high in clay and clayloam and low in sandyloam during all the two scenarios (Figure 4.9).

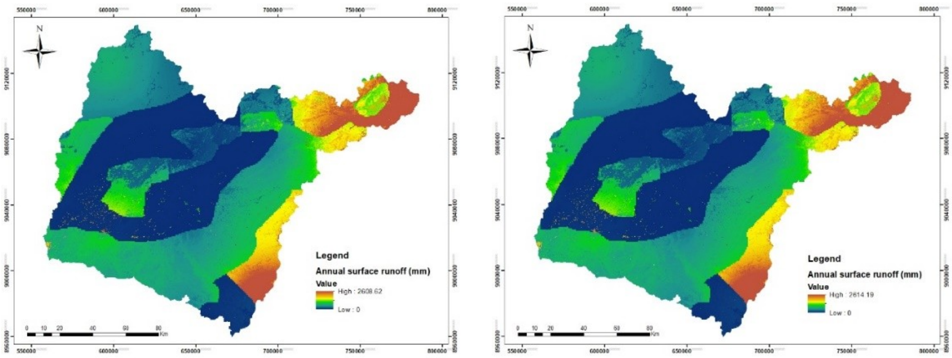


Figure 4.8: Map of annual average of SR for RCP-45 (left) and RCP-85 (right)

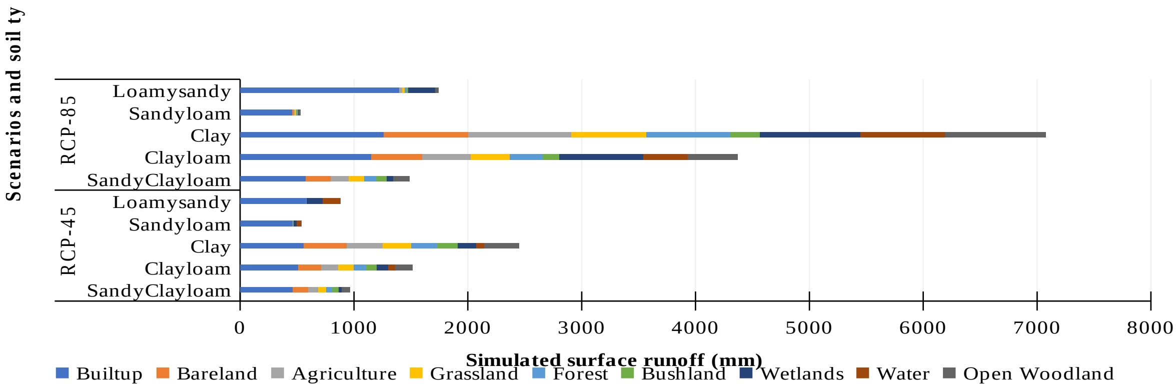


Figure 4.9: Simulated mean annual SR for combinations of LULC and soil texture

4.4.1.2 Actual evapotranspiration

The future spatial and seasonal mean average actual evapotranspiration (AET) modelled by WetSpass are presented in Figure 4.10 and Table 4.3. The projected annual averages AET are 916mm in RCP-45 and 935mm in RCP-85 which denote 61% of the mean annual rainfall in all scenarios. In RCP-45, approximately 71% (652mm) and 29% (262mm) of mean annual AET are expected in wet and dry seasons, respectively.

During RCP-85 scenario, about 70% (658mm) of mean annual AET are projected to occur in wet season and 30% (276mm) in dry season (Table 4.3). Wetlands and water bodies land cover types and loamysandy and clayloam soil types are anticipated to be generating high amount of evapotranspiration in both scenarios (Figure 4.11). On the other hand, the AET is predicted to be low in Built-up and sandyloam during both scenarios.

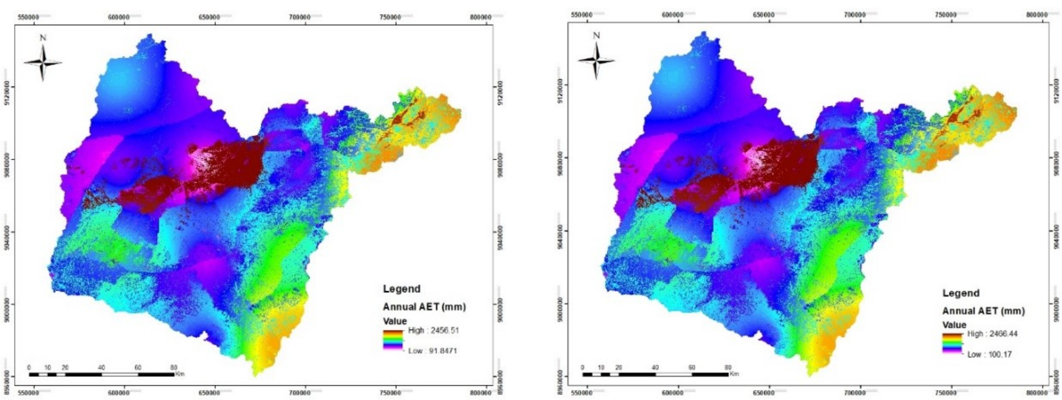


Figure 4.10: Map of annual average of AET for RCP-45 (left) and RCP-85 (right)

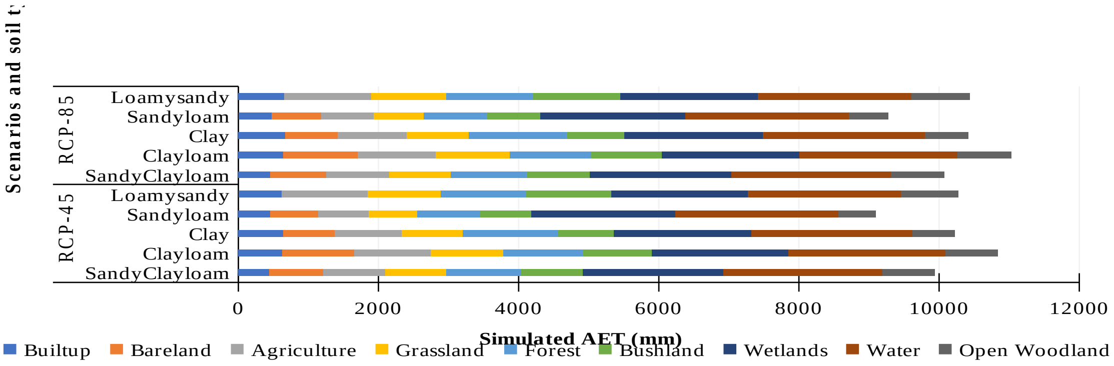
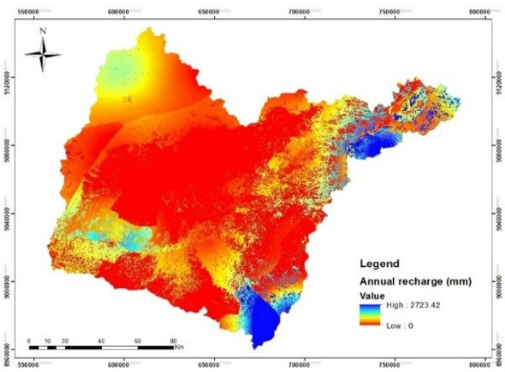


Figure 4.11: Simulated mean annual AET for combinations of LULC and soil texture

4.4.1.3 Groundwater recharge

The WetSpass model simulated the future mean annual recharge as depicted in Figure 4.12. The groundwater recharge dynamics are projected to vary spatially and seasonally. The simulations revealed that for annual, wet, and dry seasons the averages of groundwater recharge expected are 149mm, 154mm and -6mm, respectively in RCP-45. Through the RCP-85 scenario, the future averages of groundwater recharge are 150mm, 154mm and -4mm for annual, wet, and dry seasons, respectively (Table 4.3). Neary 10% of mean annual groundwater recharge are projected to be contributed by the mean annual rainfall to the groundwater storage. In the next 30 years, the maximum annual recharge will be occurring loamysandy and clayloam soil types and in open woodland and forest land cover types for the two scenarios (Figure 4.13).



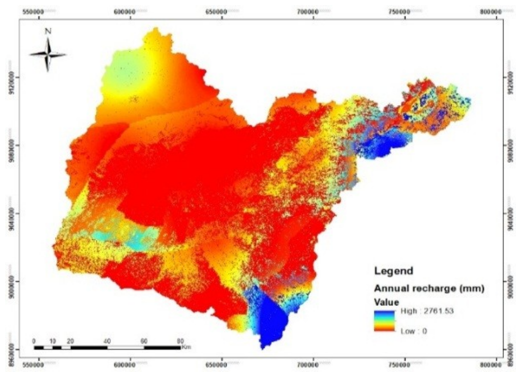


Figure 4.12: Map of annual average of Recharge for RCP-45 (left) and RCP-85 (right)

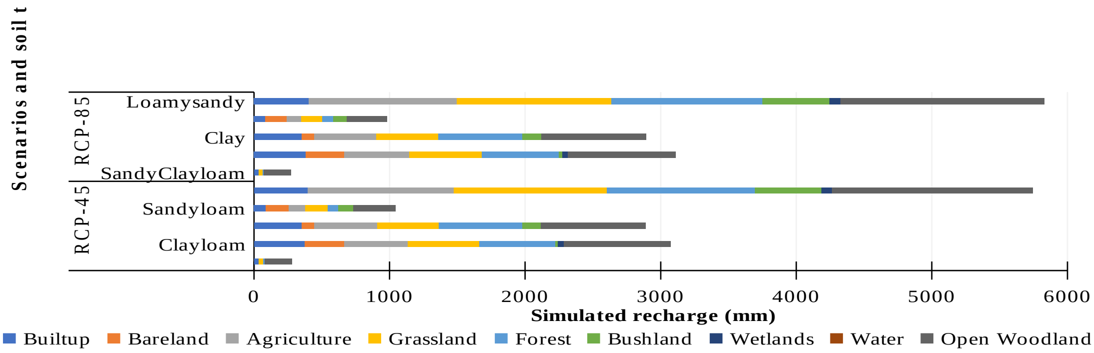


Figure 4.13: Simulated mean annual recharge for combinations of LULC and soil texture

4.4.2 Groundwater recharge potential areas

Provided the future projection of mean annual groundwater recharge (Figure 4.12), the recharge process in the Usangu Plains is predicted to vary as illustrated in Figure 4.14. Through the RCP-45 scenario, the groundwater recharge potential zone with high annual rates (663-2723mm) is expected to be 4.5% of the Usangu Plains, the zone with moderate annual rates (172-662mm) to have 25.9% and the zone with low annual recharge rates (0-171mm) to be 69.6% of the whole Usangu area. During the RCP-85, the zone with high annual recharge rates (672-2762mm) is anticipated to occupy 4.5% of the total area, the zone with moderate rates (174-671mm) to have 26.1% and the zone with low rate (0-173mm) to have 69.4%. Spatially, the groundwater recharge is predicted to be low in the central part of Usangu Plains, high in southern and some southwestern parts of the catchment while the moderate recharge is projected to occur mainly in the northeastern, southeastern and southwestern zones.

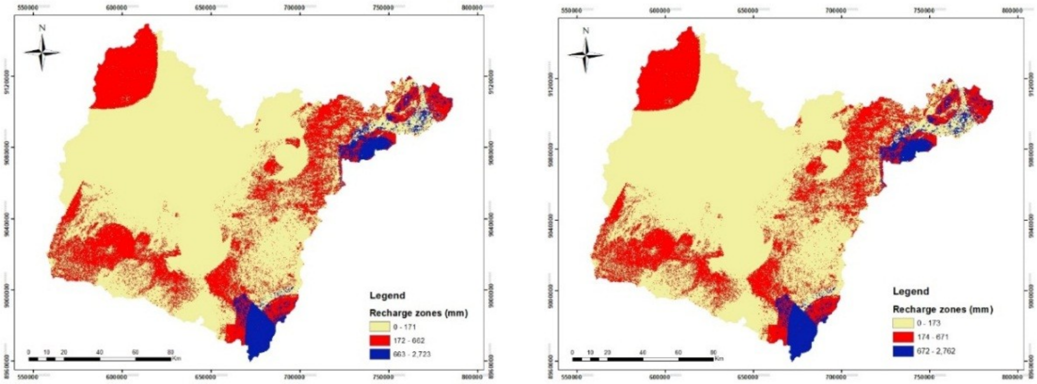


Figure 4.14: Groundwater recharge zones for RCP-45 (left) and RCP-85 (right)

4.4.3 Variability of the projected water budget components in the Usangu Plains

In the next 30 years (2021-2050), the water budget components of the Usangu Plains are expected to change, especially due to the extreme variations of precipitation (Figure 4.3)

and temperature (Figure 4.4) which affects almost all the other aspects of the water balance. The coefficient of variation (CV) is defined as the ration of the standard deviation (SD) to the mean of the data. The CV was used to determine the seasonal and annual variations of groundwater recharge, surface runoff (SR) and AET simulated by the WetSpass model against the precipitation throughout the two scenarios (Table 4.3).

Douglas *et al.* (2015) indicated that a value of CV<0.25 is considered as low variability, 0.25-0.75 as moderate variability and CV>0.75 as high variability. Also, the CV was reported better than SD to capture variations in even small mean values (Mohan *et al.*, 2018). Table 4.3 shows that in the course of both scenarios, there will be high positive variability of rainfall and surface runoff throughout all seasons. The Usangu Plains are expected to have high positive variability of recharge annually and in wet season while having high negative fluctuations of recharge in the dry season. Only the actual evapotranspiration is anticipated to vary moderately and positively during all the time spans.

Table 4.3: Projected water budget components of Usangu Plains

Scenario	Season	Dry			Wet			Annual		
	Parameter	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
RCP-45	Precipitation	363	305	0.84	1137	1005	0.88	1500	1303	0.87
	SR	77	80	1.04	150	191	1.27	227	268	1.18
	AET	262	193	0.74	652	262	0.40	916	435	0.47
	Recharge	-6	25	-4.17	154	237	1.54	149	247	1.66
RCP-85	Precipitation	390	325	0.83	1144	1004	0.87	1534	1321	0.86
	SR	82	85	1.04	152	193	1.27	234	274	1.17
	AET	276	193	0.70	658	263	0.40	935	436	0.47
	Recharge	-4	27	-6.75	154	237	1.54	150	250	1.67

4.5 Discussion

Areal-based biophysical variables (LULC, soil texture, slope, and topography) and groundwater levels were kept constant as far as this study is concerned. The influence of future climate change on groundwater recharge is predicted to be greater provided the projected variations in climate factors (Holman, 2006). However, the impacts of projected climate variability are prone to uncertainties derived from the projections of GCMs, the RCMs (RCA4 of CORDEX-Africa for this study) used for downscaling and the hydrological models (Taylor *et al.*, 2009). By the help of the WetSpass model, about 10% of the near-term mean annual rainfall was simulated as future groundwater recharge in both RCP-45 (149mm) and RCP-85 (150mm). Approximately, 15% and 61% of the future mean annual precipitation are projected to be lost through surface runoff and actual evapotranspiration, respectively in RCP-45 (227mm and 916mm) and RCP-85 (234mm and 935mm). These findings are likely similar to those of Olarinoye *et al.* (2020) conducted in Arusha-Tanzania indicating the decrease in future groundwater recharge and increase in SR and AET as a response to future climate change.

In accordance with the study of Benedict (2019) in the Usangu Plains and compared to the findings of the second chapter, the future climate variations will cause the increase of SR in the catchment. In addition, SR is expected to increase in built-up LULC type and clay soil type given their low infiltrability. Also, the high emission of greenhouse gases (example of carbon dioxide in the two scenarios, RCP-45 and RCP-85) causes the plants to not open their stomata regularly which can reduce evapotranspiration and increase surface runoff (Cao *et al.*, 2010). This increase may be the source of extreme river flooding and reduced groundwater recharge (implying decrease of baseflow) (URT, 2013), hence the declines in river discharges and irrigation water availability in the Usangu Plains.

As predicted by GCMs, though uncertain, there will be high variations of intense precipitation and temperature also in Tanzania (URT, 2012), Usangu Plains included (Table 4.3). These variations are obviously expected to affect the evapotranspiration, where it is projected to increase in both scenarios (Table 4.3). According to URT (2013), wetlands and surface water bodies are disposed to future challenges like droughts caused by the climate change. This study revealed that AET will highly increase in water bodies and wetlands LULC types (Figure 4.11). Consequently, this increase in AET, apart from negatively affecting the deep percolation, may be the reason of temporal decrease of the wetlands’ extent and affect the agro-biodiversity within the areas (URT, 2015).

The rainfall regime in the Usangu Plains is unimodal and orographic (Mutayoba and Kashaigili, 2017), meaning that the highlands will be having high and uneven distributions of rainfall intensities over the lowlands (WB, 2017) with a single rainy seasons extending from December up-to June. Depending much on rainfall (Taylor *et al.*, 2013), groundwater recharge in the Usangu Plains was found to be decreasing in the next 30 years, compared to the results of the second chapter. The high rates of groundwater recharge were projected to occur in the southwestern highlands as reported in the second chapter while low recharge is expected in lowlands as provided that lowlands are considered as discharge zone (SMUWC, 2001). This recharge, obviously driven by the alterations of rainfall amounts, time and intensity to be caused by future climate change (Cook and Vizy, 2013), was found to be about 10% of the mean annual rainfall in both scenarios. These findings of decreasing future groundwater recharge, despite the projected high intense precipitation, agree with the studies conducted in Tanzania (IUCN, 2012; Benedict, 2019; Olarinoye *et al.*, 2020 and URT, 2013) and globally (Holman, 2006 and Taylor *et al.*, 2013). The recharge zone with high rates is projected to reduce with less than 5% of the whole Usangu catchment compared to 15% found in the second chapter. The zone with low recharge rates is predicted to increase from 40% to about 70% in the near future. However, it was found in the third chapter that rivers depend greatly (about 90%) on groundwater discharges and Benedict (2019) reported unauthorized reliance on river water for irrigation. Therefore, the reduction in recharge zones caused by the unevenly distributions of future precipitations will cause much decrease of baseflow contributions to rivers and affect agricultural productivity in the Usangu watershed.

4.6 Conclusion and Recommendation

Despite reported uncertainties in climate model projections, there is an agreement that precipitation will increase and evidently affect the water budget components. The WetSpass model was used to simulate future spatial and temporal variations of groundwater recharge dynamics, surface runoff and actual evapotranspiration during RCP-45 and RCP-85 scenarios. The findings indicated that the future uneven precipitation intensities will cause the reduction of groundwater recharges zones and probably influence the declines of river water levels in the Usangu Plains. Thus, adaptation and mitigation measures to withstand the influence of future climate change in the Usangu Plains are of great help in boosting the groundwater reserve. Given the uneven distribution of projected precipitation, the application of rainwater harvesting technologies and managed groundwater recharge approaches will enhance the water availability for ecosystems, domestic and economic use in the Usangu catchment. This study considered only the variations in climate factors to simulate future recharge, the results can be altered by changes in other socio-economic variables. Therefore, further studies are recommended to take into consideration future changes in LULC, urbanization, demography, slope and soil texture to simulate accurately their impacts on the water budget components in the Usangu catchment.

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CHAPTER FIVE

5.0 General Conclusions and Recommendations

5.1 Conclusions

This study was conducted in the Usangu plains, Tanzania, with a general objective of modelling the interactions between groundwater and surface water and the groundwater recharge dynamics. This study had three specific objectives namely: (1) to evaluate groundwater recharge dynamics in the Usangu Plains using the WetSpass model, (2) to analyze the water exchange processes between groundwater and surface water in the Usangu Plains and (3) to evaluate the future climate change influence on groundwater recharge in the Usangu Plains.

The findings showed that about 13.1% of the mean annual rainfall recharge the groundwater storage while 14.5% and 76.8% go to surface runoff and actual evapotranspiration, respectively. However, the future climate change was simulated to affect the water budget components by decreasing the groundwater recharge magnitude and distributions while increasing the SR and AET portions. The Estimation of the safe yield of the groundwater systems recharge in terms of fraction (approximately 10%) of the pre-development recharge flux (annual average) has been used here as a quick simplistic approach that is, however, inherently flawed and inconsistent with the complex operation of the groundwater systems. More detailed studies beyond the scope of this thesis are required to understand how shallow groundwater systems in the Upper Great Ruaha respond to pumping and the dynamics of groundwater storage (i.e., how wells sustain themselves by altering subsurface flow patterns). Furthermore, it is vital to recognize that in semi-arid lowlands like the Usangu Plains, the sustainability of groundwater withdrawals is inherently connected to surface waters through either focused recharge or capture through induced leakage of surface flows to the groundwater system.

5.2 Recommendations

According to the results of this study, the following recommendations can be formulated:

i. Local police-makers and all water-centered stakeholders have to take the lead in the initiation of artificial or managed groundwater recharge strategies with the main focus in the zones with low and moderate recharge rates to boost the groundwater storage.

ii. Further studies about the relationship between groundwater withdrawals and recharge dynamics and the related consequences in the Usangu Plains are recommended.

iii. Exhaustive studies are needed to generate a clear understanding of what type of groundwater recharge, focused or diffuse, dominate in either the uplands or the lowlands of the Usangu Plains.

iv. For a flawless comprehension of the groundwater-surface water interactions, it is advised to position observation wells not far away (at most 2 km) from the river gauging stations.

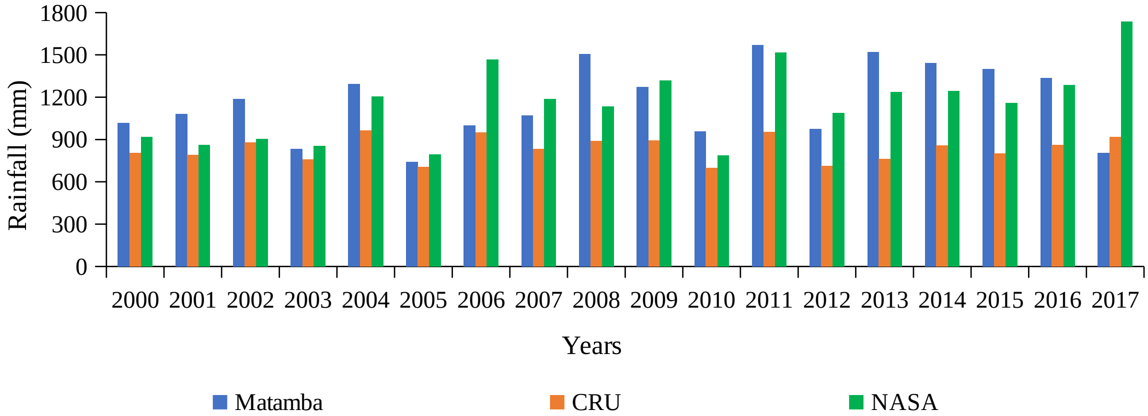
v. The trend analysis performed by the help of Mann-Kendall test revealed non-significant statistical variations of the river flows, however, this was due to the lack of long-term data. So, the use of long-term (at least 30 years) river discharge data for the trend analysis in the river flows and baseflow, hence detect their relationship.

vi. Effective policies for adaptation and mitigation approaches will help to counteract and withstand the devastating influence of climate change and variability.

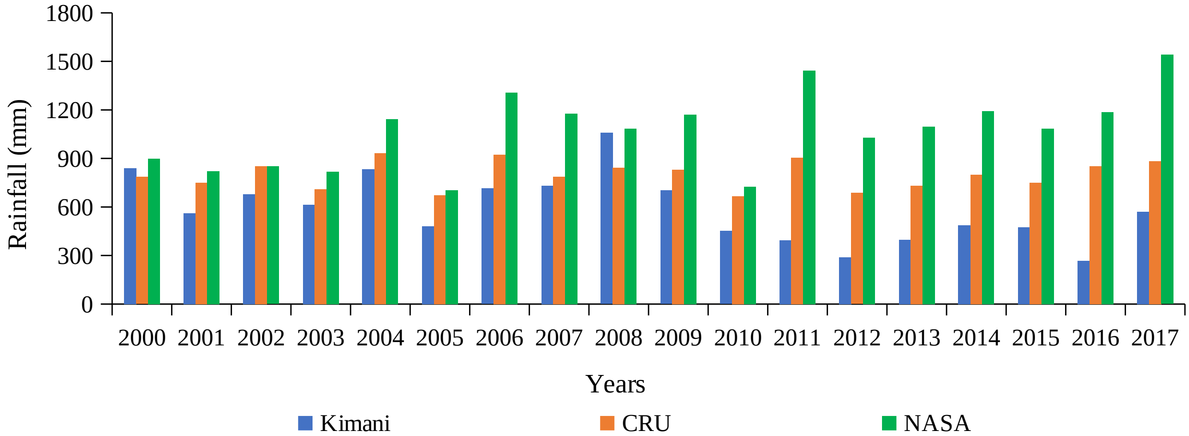
APPENDICES

Appendix 1: Comparative analysis of rainfall data

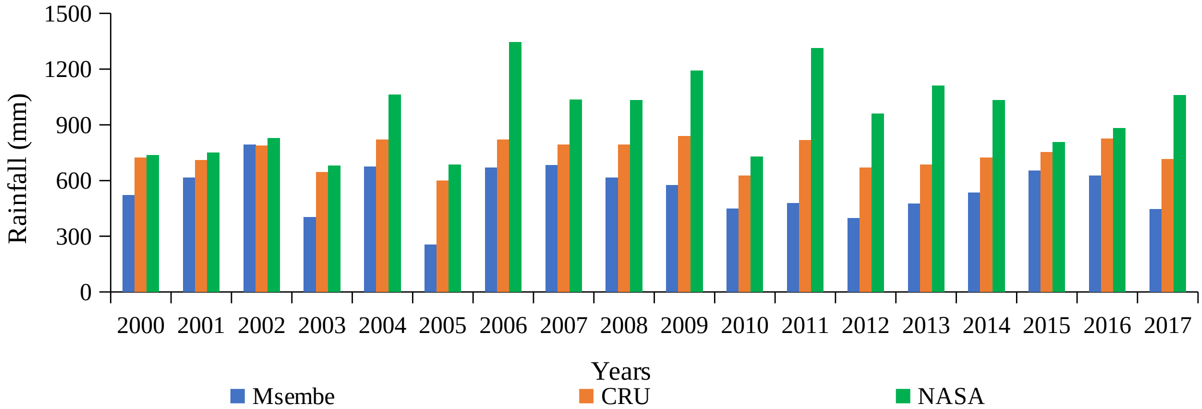
(a)



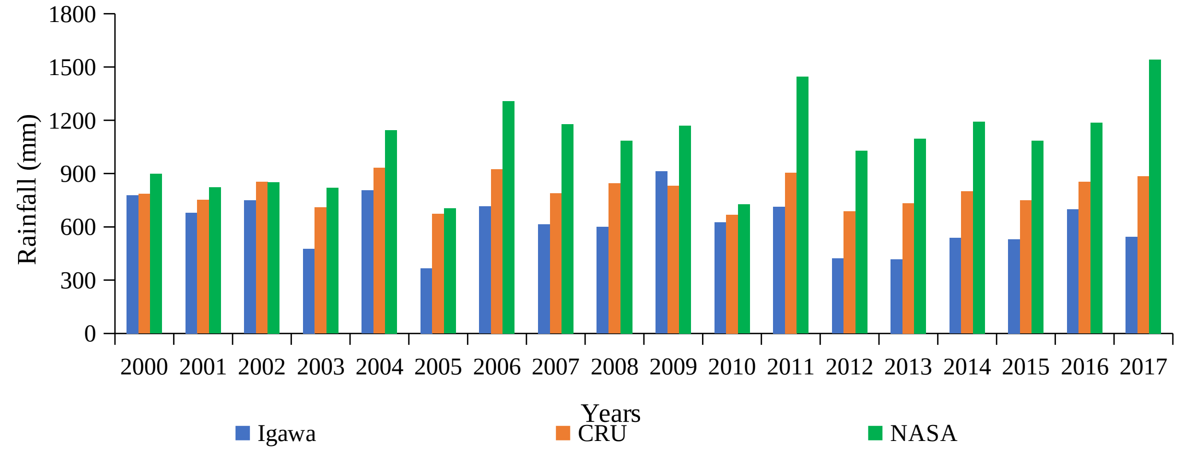
(b)



(c)



(d)



(a)			(b)			(c)			(d)		
Station	Lat	Lon	Station	Lat	Lon	Station	Lat	Lon	Station	Lat	Lon
Matamba	-8.53	33.60	Kimani	-8.83	34.17	Msembe	-7.72	34.90	Igawa	-8.71	34.38
CRU	-8.75	33.75	CRU	-8.75	34.25	CRU	-7.75	33.75	CRU	-8.75	34.25
NASA	-8.75	33.75	NASA	-8.75	34.25	NASA	-7.75	33.75	NASA	-8.75	34.25

Appendix 2: Algorithms of the hydrograph separation techniques

1. Fixed interval method

The Fixed interval (FI) method assigns the lowest discharge in each interval (I) to all days in that interval starting with the first day of the period of record. The method can be visualized as moving a bar 2I days wide upward until the bar first intersects the hydrograph. The discharge at that point is assigned to all days in the interval. The bar is then moved 2I days horizontally, and the process is repeated. The assigned values are then connected to define the base-flow hydrograph (Sloto and Crouse, 1996).

2. Sliding interval method

The Sliding Interval (SI) method finds the lowest discharge in one half the interval minus 1 day [0.5(2I-1) days] either side of the day being considered and assigns it to that day. The method can be visualized as moving a bar 2I wide upward until it intersects the hydrograph. The discharge at that point is assigned to the median day in the interval. The bar then slides over to the next day, and the process is repeated (Sloto and Crouse, 1996).

3. Local minimum method

The Local Minimum (LM) method checks each day to determine if it is the lowest discharge in one half the interval minus 1 day [0.5(2I-1) days] before and after the day being considered. If it is, then it is a local minimum and is connected by straight lines to adjacent local minimums. The base-flow values for each day between local minimums are estimated by linear interpolations. The method can be visualized as connecting the lowest points on the hydrograph with straight lines (Sloto and Crouse, 1996).