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Assessment of Climate Change's Impacts on River Flows in the Songwe Sub-Basin

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Abstract

River flow in the Songwe sub-basin is predicted to alter due to climate change, which would have an impact on aquatic habitats, infrastructure, and people's way of life. Therefore, the influence of climate change should be taken into account when making decisions about the sustainable management of water resources in the sub-basin. This study looked into how river discharge would react to climate change in the future. By contrasting hydrological characteristics simulated under historical climate (1981-2010) with projected climate (2011-2040, 2041-2070, and 2071-2100) under two emission scenarios, the effects of climate change on river flow were evaluated (RCP 4.5 and RCP 8.5). The ensemble average of four CORDEX regional climate models was built to address the issue of uncertainty introduced by the climate models. The SWAT model was force-calibrated using the results from the generated ensemble average for the RCP 4.5 and RCP 8.5 emission scenarios in order to mimic the river flow during past (1981-2010) and future (2011-2100) events. The increase in river flows for the Songwe sub-basin is predicted to be largest during the rainy season by both the RCP 4.5 and RCP 8.5 scenarios. Under RCP 8.5, the abrupt decrease in river flow is anticipated to reach its maximum in March 2037, when the discharge will be 44.84 m^3/sec, and in March 2027, when the discharge will be 48 m^3/sec. The extreme surge in river flow will peak, according to the RCA4, in February 2023, in April 2083 under RCP 4.5, and, according to the CCLM4 and RCA4, in November 2027 and November 2046, respectively. The expected decrease and increase in river flow throughout both the dry and wet seasons may have an impact on the management of the sub-water basin's resources, biodiversity, and hydraulic structures. The right adaptations and mitigation strategies should be adopted in order to lessen the negative consequences of climate change on precipitation, temperature, and river flow in the sub-basin.

Keywords

Climate Change, Climate Models, Songwe River Sub-Basin, River Flow, SWAT

1. Introduction

The world is dealing with an increase in sediment output and a shortage of water resources for social-economic activities as a result of rising population and land use activities [1]. The hydrological cycle is altered as a result of climate change, which also has an impact on the environment and human life worldwide [2]. The Intergovernmental Panel on Climate Change (IPCC) anticipated that the world's temperature will rise by 1.5˚C in its Sixth Assessment Report (AR6) [3]. It is beyond dispute that human activity is driving climate change, resulting in extreme weather events like heatwaves, torrential downpours, and droughts, and impacting every corner of the planet in various ways [3]. Tanzania is one of the developing nations that are experiencing the effects of climate change on its water, sediment yield and agricultural industries [4]. These effects result in modifications to the catchment's runoff volume, streamflow volume, soil moisture, soil erosion, and sediment yield [5]. One of the most noticeable aspects of the changing climate that directly affects all hydrological responses in the catchments is the rise in surface air temperature and rainfall patterns [6]. Small alterations in the global climate across eastern and southern Africa have a significant impact on the regional climate [7]. Most regions are subject to variations in temperature and rainfall patterns because hydrological conditions vary from region to region [8]. Strong agreement was found between the 34 climate models used in Future Climate for Africa (FCFA) 2017 regarding Tanzania's continued warming in the range of 0.80 C to 1.80 C by the 2040s [9], which will cause an increase in annual evapotranspiration, unbalanced atmospheric moisture, and changes in the hydrological cycle of the ecosystems [10].

Currently, it is crucial to evaluate how climate change may affect local and regional water resources. Changing river flow conditions are a key effect of climate change on Tanzania's water resources [9]. River flow changes are mostly brought on by variations in the water balance, such as precipitation and temperature [11]. Many researchers have combined future projected climate data from climate models with hydrological models to assess how future runoff would respond to climate change [12]. Studying the effects of climate change on river flows involves using global climate model (GCM) or regional climate model (RCM) climate change scenarios [13]. In the Little Ruaha catchment, Nobert (2022) evaluated the expected changes in streamflow brought on by upcoming climate change for the years 2025-2060. The RCP4.5 and RCP8.5 greenhouse gas concentration scenarios and General Circulation Model (GCM) datasets from the ACCESS1.0, CNRM-CM5, and BCC-CSM1 models were chosen as the representative scenarios. The calibrated NAM hydrological model was used to analyze the effect of climate change on stream flows. The impact assessment findings indicate that for both the RCP4.5 and RCP8.5 scenarios, the monthly maximum and minimum temperatures will rise in the range of 0.8˚C to 2˚C under the climate change scenario (2025-2060). In the case of rainfall, an average yearly increase in rainfall of around 10% over the baseline is anticipated. The inter-annual variability of rainfall for the years 2025 to 2060, however, indicates a declining trend for RCP 8.5. According to the simulation results, streamflow for RCP4.5 and RCP8.5 will fall by around 30% and 6%, respectively.

The effects of climate change on hydrological responses and sediment yield in the Songwe sub-basin and Lake Rukwa Basin have not been discussed in any of the research. This study used high-resolution climate and spatial data, as well as the Soil and Water Assessment Tool (SWAT), to evaluate the effects of climate change on the streamflow of the Songwe sub-basin in the Lake Rukwa Basin. In this work, data from the ensemble of the CORDEX Africa regional climate model (RCM) have been conducted under RCP 4.5 and 8.5 out of four potential emission scenarios of RCP 2.0, RCP 4.5, RCP 6.0, and RCP 8.5. These were added to the hydrological model once they had been calibrated and verified. The RCP 4.5 scenario depicts the approach to the radiative forcing trajectory that stabilizes without overshoot and leads to a peak level of 4.5 W/m^2 [14]. According to the RCP 8.5, the radiative forcing will increase and reach 8.5 W/m^2 by 2100 [2]. The focus of this study was therefore to assess the impacts of climate change on river flows under RCP 4.5 and 8.5.

2. Materials and Method

2.1. Description of the Study Area

The Songwe sub-basin (**Figure 1**) covers an area of roughly 10,800 km^2 and is situated in the eastern portion of the Lake Rukwa Basin in southern-western Tanzania. It is found between latitudes 07˚40'S and 09˚20'S and longitudes 33˚00'E and 33˚50'E. All river catchments that pour into Lake Rukwa have one outlet, describing an internal drainage system. There are various hills in the area that cuts through fertile valleys, and their elevations range from 600 to 2400 masl. The catchment is distinguished by generally healthy, fertile soils, consistent, and copious amounts of precipitation, mild temperatures, and excellent agricultural potential. According to the 2012 National Census, the sub-basin has a population of roughly 843,278 people, 40% of whom reside in Mbeya City and the adjacent peri-urban areas. By 2035, the sub-basin population is expected to increase to around 1,643,629 people. One of Tanzania's most productive regions is the Songwe watershed. About 80% of the population works in agriculture is the primary industry. Mbeya City, a significant regional economic and industrial hub, is also located within the watershed.

Due to topographical height, differences in rainfall distribution based on time

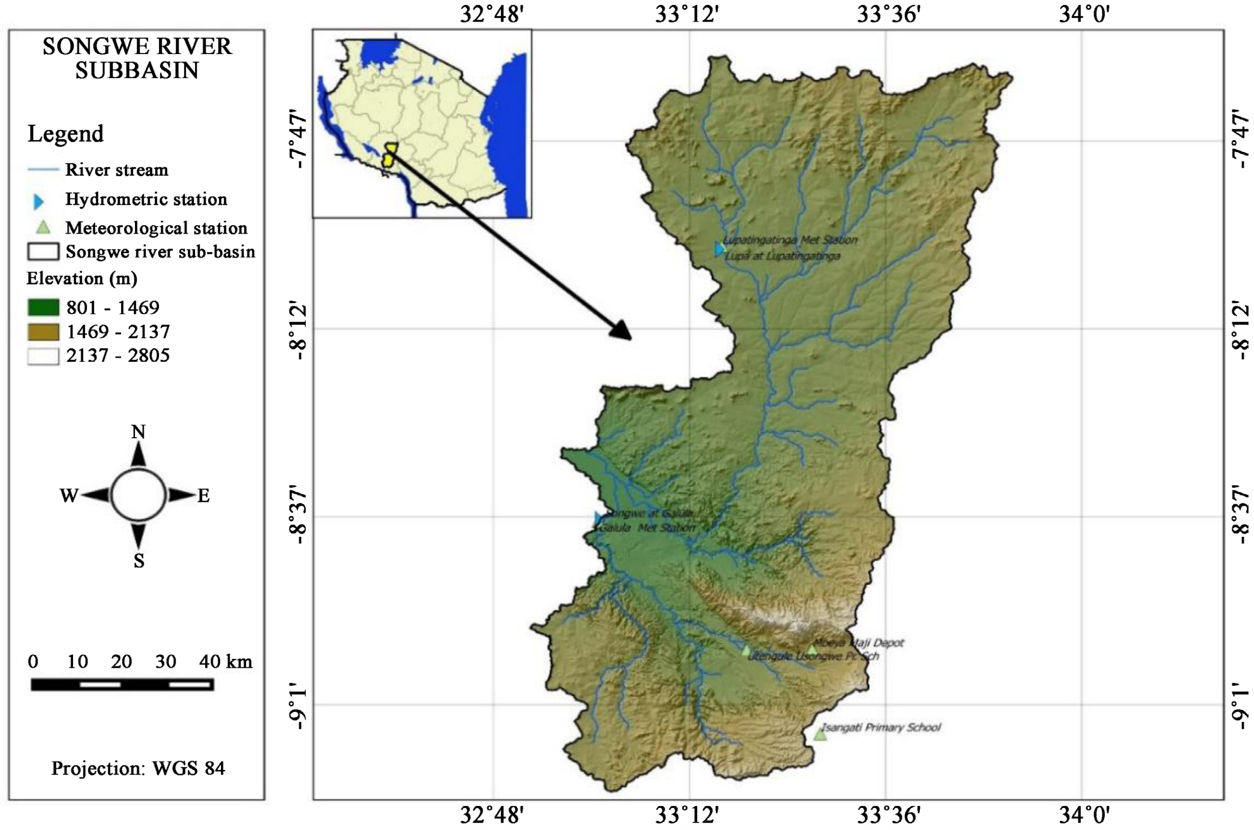


Figure 1. Location of the Songwe sub-basin.

and place, and related land use activities that occurred in the sub-basin that influenced river flow, soil erosion, and sediment yield to rivers and Lake Rukwa, the Songwe sub-basin has a diverse bioclimate. The sub-basin primarily has a tropical climate and has one extended rainy season (October to May). From about June to September, there is a dry period. The lowlands receive 650 mm of annual precipitation, while the highlands receive 2600 mm. The altitude-dependent mean temperature ranges from about 16˚C in the highlands to roughly 30˚C in the lowlands. Three significant rivers drain the northern, central, and southern portions of the Songwe Sub-basin: the River Lupa, the River Songwe, and the River Zira, which originate in the Poroto Mountains and drain the southern portion. The rivers travel through the gold mine area, crossing wide flat lowlands, combining, and then emptying into Lake Rukwa. Strong seasonality is present in all sub-basin rivers, with high flows during the rainy season and low flows during the rest of the year. The rivers see their highest flows between February and March and their lowest flows between July and November, with September being the driest month. Climate change, which has led to significant fluctuations in temperature and precipitation and has serious effects on the management and use of the sub-basin water resources, has made the issue worse.

2.2. Spatial, Meteorological, and Hydrological Datasets

The stream network and hydrologic response units are easier to define in the

SWAT model simulation due to the streamflow data, topographic features, and spatial distribution of land cover/use and soil types. The Ministry of Water Tanzania's Lake Rukwa Water Basin office provided the daily streamflow information for the Songwe sub-basin at Galula station. One of the essential inputs used by SWAT to divide the sub-basin into smaller sub-basins and to examine the sub-drainage basin's pattern, slope, stream length, and channel width is the Digital Elevation Model (DEM). In this investigation, a DEM with a 30 m spatial resolution was collected from the Advanced Land Observing Satellite Phased Array L-band Synthetic Aperture Radar (ALOS PALSAR) at the Alaska Satellite Facility, which may be found online at http://www.asf.alaska.edu. Images of land use and land cover (LULC) for the year 2020 used in this study were downloaded for free from the United States Geological Survey (USGS) website at https://earthexplorer.usgs.gov/, and categorized in line with the input specifications of the SWAT model. From the FAO-UNESCO Soil Map of the World, Volume VI at https://swat.tamu.edu/data/ online, a soil map was constructed. The water balance model in SWAT depends on data on daily precipitation, maximum and minimum air temperatures, relative humidity, wind speed, and solar radiation. Data on the daily rainfall, were gathered from the Ministry of Water's Lake Rukwa Water Basin office. While data on the minimum and maximum temperatures, solar radiation, wind speed, relative humidity, and wind direction were obtained from the updated Global Weather Database for SWAT. The Lake Rukwa Water Basin office provided daily baseline data for the Lupa tinga tinga and Galula stations. The baseline scenario was examined and calibrated using data from the baseline era, which ran from 1981 to 1992.

2.3. Climate Change Data output and Bias Correction

The CORDEX-Africa runs of the Climate Model Intercomparison Project Phase 5 (CMIP5) were downscaled from GCMs utilized in this study [8]. The Consortium for Small-scale Modeling (COSMO), Climate Limited-Area Model (CCLM), SMHI Ross by Centre Regional Climate Model (RCA4), Max Planck Institute Regional Model (REMO), KNMI-Regional Atmospheric Climate Model (RACMO22T), and High-Resolution Limited Area Model (HIRHAM5) are some of the most well-known CORDEX RCMs used in Africa [7]. For this investigation, the four RCMs produced through the CORDEX-Africa Data Search (HIRHAM5, CCLM4, RACMO22T, and RCA4) were employed (**Table 1**). RCMs used in this work have a 0.44 degree grid spacing (50 km of resolution). The reference period is changed to reflect the period of observations that are available (1981-1992). Using the spatial resolution of 0.44˚ and the RCP4.5 and RCP8.5 emission scenario paths, an ensemble mean from the regional climate models CORDEX Africa [15] was taken at the model boundaries. The Earth System Grid Federation-Lawrence Livermore National Laboratory website, https://esgf-node.llnl.gov/projects/esgf-llnl/, is where the CORDEX data were obtained. In the context of the Coordinated Regional Climate Downscaling

Table 1. The CORDEX-RCMs and their driving GCMs.

S/N	RCM	Mode Centre	Short name	GCMs
1	DMI HIRHAM5	Danmarks Meteorologiske Institut (DMI), Denmark	HIRHAM5	ICHEC
2	CLMcom COSMO-CLM (CCLM4)	Climate Limited-Area Modelling (CLM) Community	CCLM4	MPI ICHEC CNRM
3	KNMI Regional Atmospheric Climate Model, version (RACMO2.2T)	Koninklijk Nederlands Meteorologisch Instituut (KNMI), Netherlands	RACMO22T	ICHEC
4	SMHIRossby Center Regional Atmospheric Model (RCA4)	Sveriges Meteorologiska OchHydrologiska Institut (SMHI), Sweden	RCA4	MPI ICHEC CNRM

Experiment [12], the ensemble means data are available over Africa at 0.44˚ resolution, and they have already been used over Africa. The studies of the data concentrated on the future eras and the reference period (1981-1992) (2011-2100). Climate model data for hydrologic modeling (CMhyd) for four RCMs outputs and give climate data for the SWAT model were bias-corrected by the linear scaling method because precipitation and temperature are the main drivers of the hydrological regime of climate change. For the bias correction of the four RCMs' output of climate data, data on precipitation measured at gauging stations in the sub-basin and the on minimum and maximum temperature gathered from SWAT Global Weather Data were used.

2.4. Hydrological Modeling

SWAT Model Selection, Set up, and Calibration

In vast catchments with changing soils, land use/land cover, and management conditions, the SWAT model uses a physically-based, semi-distributed approach to anticipate the effects of land management methods on water, sediment, and nutrients [16]. Comprehensive data on the weather, soil characteristics, and terrain, vegetation, and land management techniques are required for the SWAT model [17]. The SWAT model was used to simulate the water balance for the chosen period and under changing climatic conditions [18]. [16] provides a thorough explanation of the SWAT model. The DEM-derived drainage patterns that the model uses to construct small sub-basins that are then divided into smaller sub-basins by a threshold that specifies the required amount of drainage to create a stream [19]. Hydrologic response units (HRU) with unique LULC classes, soil types, and slope classes are created from these small sub-basins [20]. Each hydrologic response unit runoff is anticipated independently and routed to determine the sub-overall basin's runoff. In general, the SWAT model integrates climatic station data at the sub-basin while solving the water balance equation for each HRU and adding the HRU calculations for each sub-basin [16]. For each HRU, the hydrological balance is simulated using the water balance equation [16]. The Songwe sub-basin, which has an extent of around 10,800 km^2, is one of the catchment that the SWAT model can be applied to. The application addresses the bias-correction of RCMs temperature and precipitation, as well as the development, calibration, and validation of the SWAT model for the Songwe sub-basin and the forced simulation of the model using a set of bias-corrected RCM outputs to evaluate future climatic and river flow change for the years 2011-2100. Galula station streamflow data from 1981 to 1992 were used to assess the model's calibration and performance. Due to its ability to physically foundation and continually simulate hydrological processes, the SWAT model was chosen for this study. These characteristics are crucial for modeling the effects of climate change on streamflow. The model can calculate the basin's hydrologic water cycle by integrating various spatial data, observed data, and anticipated climatic data (Arnold *et al.*, 2012), which makes it valuable for catchment management. The SWAT is a hydrological model with a physical foundation that integrates with QGIS. For the model setup in this study, QSWAT 1.7 version, compatible with QGIS 2.6.1 interface, was employed. Spatial, hydrological, meteorological, and projected climate data were among the inputs gathered to create the model. **Figure 2** shows satellite pictures of land use and land cover,

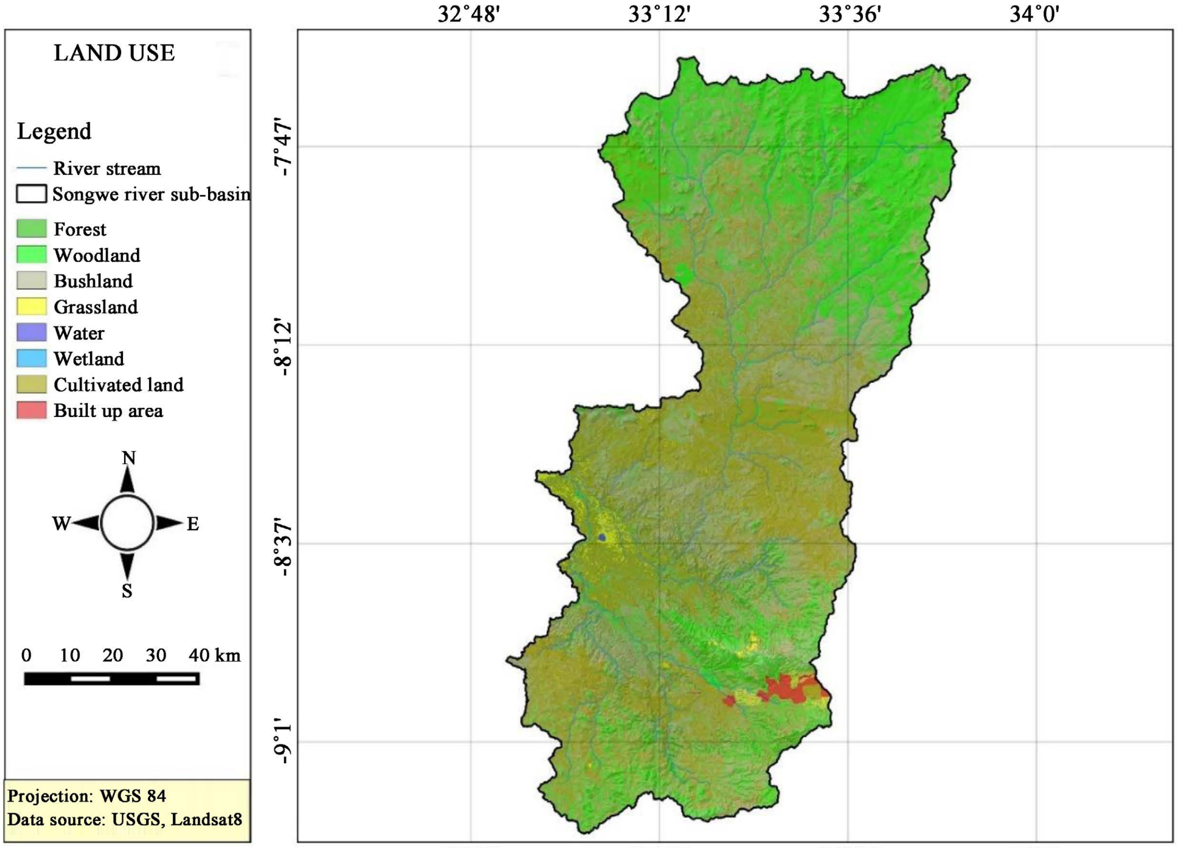


Figure 2. Land use/cover of Songwe sub-basin.

Figure 3 shows a digital elevation model with a 30 m resolution, and Figure 4 shows a soil map of the Songwe sub-basin. Figure 5 depicts the placement of the metrological and hydrological stations. Table 2 in Figure 2 displays the land use/cover in the Songwe sub-basin. The DEM and river channels of the study area served as the foundation for the model setup.

Water Balance Equation;

$$SW_t = SW_o + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{sweep} - W_{gw}\right)t \tag{1}$$

SW_t is the final soil water content,

SW_o is the initial soil water content on day i in mm,

R_{day} is the amount of precipitation on day in mm,

Q_{surf} is the amount of surface runoff on day i in mm,

E_a is the amount of evapotranspiration on day i in mm,

W_{sweep} is the amount of water entering the vadose zone from the soil profile on day i in mm,

W_{gw} is the amount of return flow on day i in mm,

t is the time in da.

The land phase of the hydrological cycle and the water phase of the hydrological cycle are the two stages of the SWAT. The process of water transportation through the stream network was chosen for this study's focus area: the water

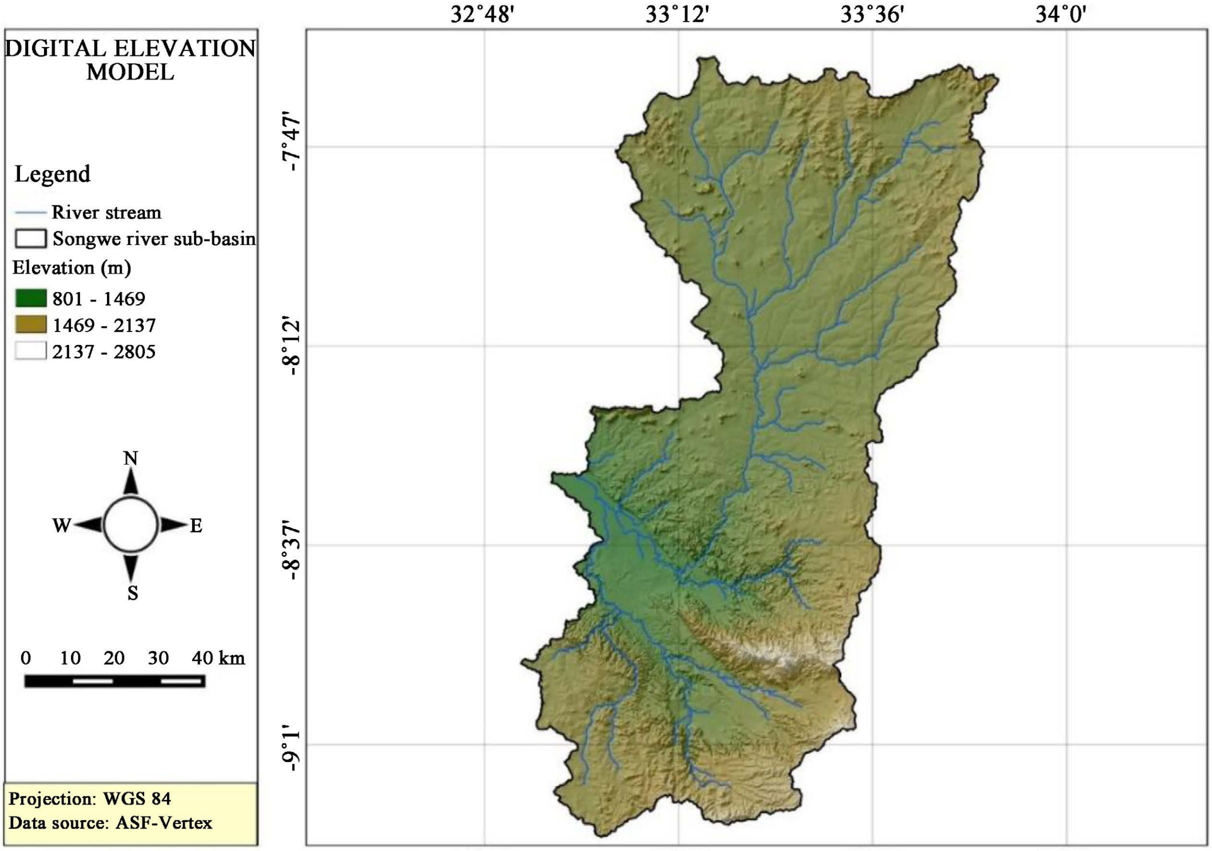


Figure 3. Digital Elevation Model of Songwe sub-basin.

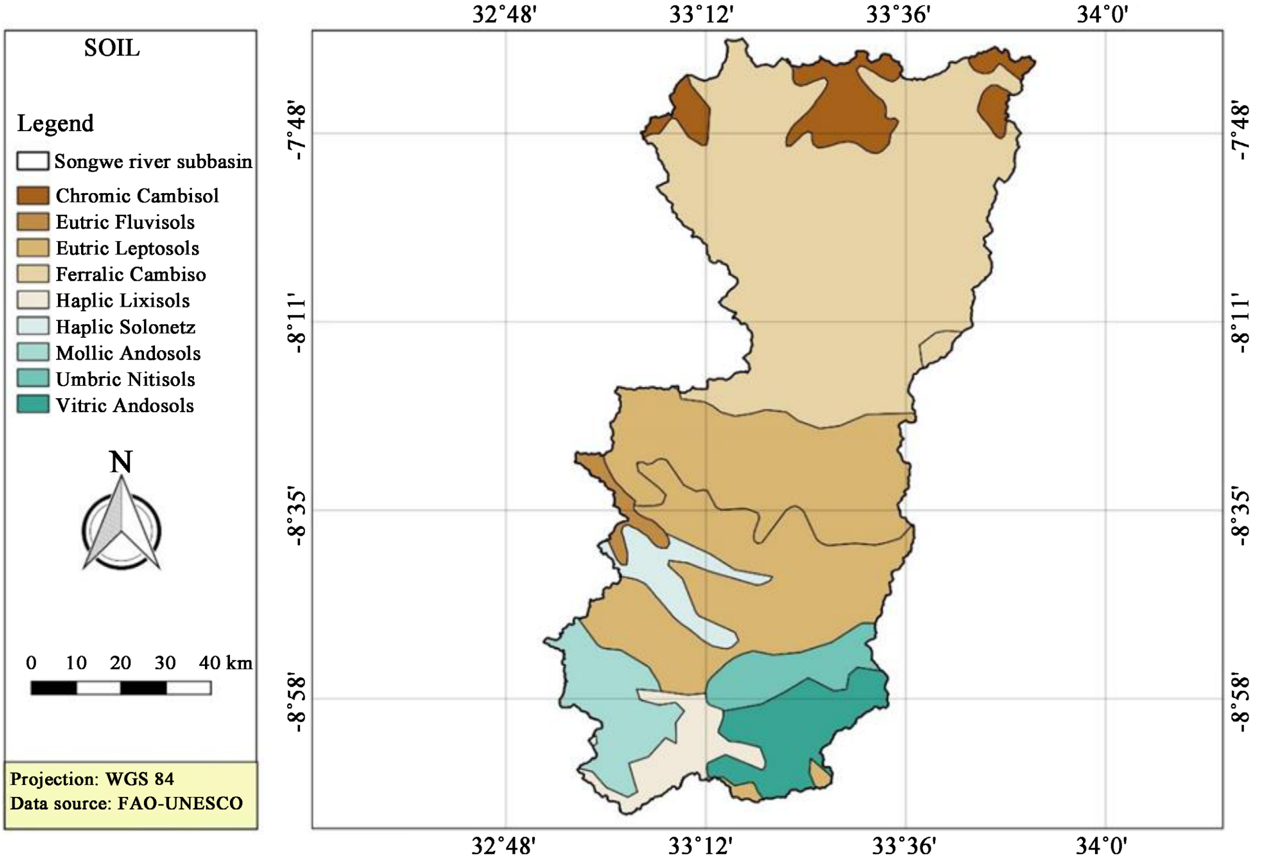


Figure 4. Soil map of Songwe sub-basin.

phase. Additionally, the SWAT model employed the Penman-Monteith model to estimate potential evapotranspiration [14]. The total volume of surface runoff was calculated using The Curve Number (CN), which requires daily precipitation data. The Songwe sub-basin was divided into several smaller sub-basins for the SWAT model, and these smaller sub-basins were then separated into units with distinctive soil and land use characteristics called hydrological response units (HRUs). These HRUs are described as homogeneous spatial units with comparable hydrological and geomorphological characteristics [1]. The sub-basins were then divided into a total of 345 hydrologic response units based on land use, soil type, and slope (HRUs). The model was first filled with the reclassified land use, land cover, and soil data before the HRUs were specified. The climatic data were entered into the model and written using the SWAT Model's Write SWAT Input Tables interface. The Write SWAT Input Tables interface of the SWAT Model was used to load and write the model's climate data, which included precipitation (pcp), temperature (tmp), relative humidity (rh), solar radiation, and wind speed. The SWAT model was run once the model's settings were modified and tables for observed weather data had been produced.

The goal of model calibration is to optimize the model's agreement with a collection of experimental data by adjusting a set of parameters. It involves changing model parameters based on comparing outcomes to observations in

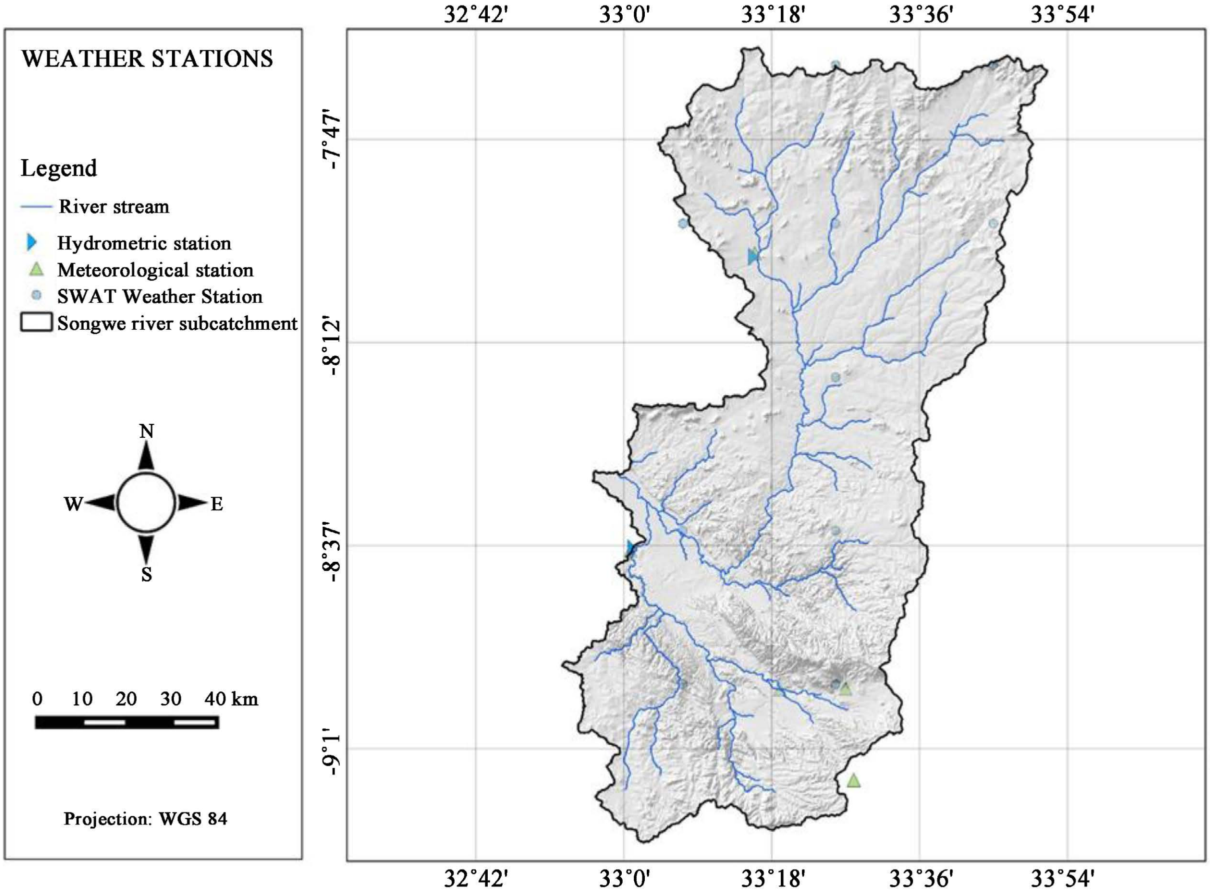


Figure 5. Weather data station in Songwe sub-basin.

Table 2. Land use/cover coverage in Songwe sub-basin.

Land use/cover	Coverage (Ha)	Percentage (%)
Forest	19,721	1.83
Woodland	326,133	30.30
Bushland	375,031	34.84
Grassland	13,441	1.25
Water	365	0.03
Wetland	190	0.02
Cultivated land	333,252	30.96
Built up area	8326	0.77

order to maintain the same response over time. From the standpoint of the model's intended usage, validation is the act of assessing how accurately a model represents the real world. Using observed streamflow data from Galula station for the years 1981 to 1992, the model was calibrated and validated. The SWAT-Calibration and Uncertainty Program's Sequential Uncertainty Fitting version 2 technique (SUFI-2) was used to identify and calibrate the SWAT model's sensitive parameters (SWAT-CUP). The SWAT model had to simulate flows with bias-corrected temperature and rainfall over the future periods and in the baseline period after being calibrated and validated using data on observed stream flows. In accordance with four regional climate models, the simulated stream flows for the 2040s, 2070s, and 20100s correspond to two scenarios.

3. Results and Discussion

3.1. SWAT Model Calibration, Validation, and Performance

The Galula gauging station in the Songwe sub-basin served as the calibration and validation site for the semi-distributed SWAT hydrologic model. With goodness-of-fit values of NSE 0.45, R^2 0.59, and RSR 0.73 for the calibration period and NSE 0.59, R^2 0.59, and RSR 0.64 for the validation period, the model was able to mimic stream flows. Table 3 shows that stream flows from the Songwe sub-basin could be simulated by the model.

The parameters utilized for the SWAT model's calibration were subjected to a global sensitivity analysis using the SWAT-CUP. The findings demonstrated that the stream flow calibration's sensitive parameters included CN2, SOL AWC, GWQWN, GW DELAY, and GW REVAP (Table 4).

3.2. Climate Change Impact in the Songwe Sub-Basin

3.2.1. Changes in Future Precipitation and Temperature

The four regional climate models' projections of average monthly mean precipitation for the historical, near-future, mid-future, and end-of-century periods were contrasted with actual observations from the base period and meteorological data produced by SWAT. Most months of the year in CCLM4, HIRAM5, RACMO22T, and RCA4 for the historical simulation of climate models in the

Table 3. Evaluation statistics for calibration and validation.

Flow Station	CALIBRATION				VALIDATION				CALIBRATION		VALIDATION	
	NSE	R^2	RSR	PBIAS	NSE	R^2	RSR	PBIAS	Ob-flow (m^3/s)	Sim-flow (m^3/s)	Ob-flow (m^3/s)	Sim-flow (m^3/s)
Galula	0.47	0.59	0.73	−35.5	0.59	0.59	0.64	3.9	33.16	44.9	33.16	31.88
Lupa	−0.09	0.01	1.04	−17.1	−0.08	0.01	1.04	9.1	93.30	109.22	93.30	84.80

Ob-flow; Observed flow. Sim-flow; Simulated flow.

Table 4. Most sensitive parameters and their fitted values.

Rank	Parameter	Parameter definition	Fitted value
1	CN2.mgt	SCS runoff curve number	0.00000000
2	SOL_AWC.sol	Available water capacity of the soil layer	0.00000143
3	GWQWN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur	0.00306594
4	GW_DELAY.gw	Groundwater delay	0.00417118
5	GW_REVAP	Groundwater "revap" coefficient	0.10412491

sub-basin are characterized by an overestimation of the observed precipitation in all stations (**Figure 6**). The bias-corrected Regional climate models output for historical revealed that, in the majority of the stations under study, the CCLM4 and HIRAM5 models outperformed the RCA4 and the RACMO22T models in terms of their ability to replicate the observed mean monthly rainfall. In accordance with the RCP 4.5 climate scenarios, the four climate models predict that the amount of precipitation over the sub-basin will decrease in the months of January, February, March, April, and November, increase in the month of December during the early part of the century, and decrease in the month of December for the mid and late parts of the century. Under RCP 4.5, the RCA4 and RACMO22T models predicted more precipitation than the CCLM4 and HIRAM5 RCMs (**Figure 7**). All four climate models predict a rise in precipitation over the sub-basin in January, February, March, April, November, and December under the RCP 8.5 warming scenarios, and a decrease in April. Also, except for January, March, and April for the Galula Station, drop for January, February, March, and November. Increase for December for the mid- and end-century periods for all four RCMs. Under RCP 8.5, the RCA4 and RACMO22T models predicted more precipitation than the CCLM4 and HIRAM5 RCMs (**Figure 8**). All four climate models predict an increase in temperature over the sub-basin during the early, mid, and end periods of the century under both the RCP 4.5 and RCP 8.5 climate scenarios. For Galula station in the Songwe sub-basin, all regional climate models predicted a rise in the lowest and maximum temperature in both the historical and future climate (**Figure 9**). Future months with high temperatures include September, October, November, and December.

3.2.2. Climate Change Impacts on River Flow

River flows alter as a result of climate change's impact on various water balance components. Accordingly, under the two RCP scenarios, changes in river flows are anticipated in the sub-basin following the change in temperature. The calibrated SWAT model was used to simulate the anticipated river flows for the first, middle, and last decades of the century using the output from the four Regional Climate Models that had been bias-corrected. In the sub-basin, the effects of the changing climate were evaluated. It has been shown how the river flows under RCPs 4.5 and 8.5 between the historical and future periods (**Figure 10**). Both the RCP 4.5 and RCP 8.5 scenarios predict that the rise in river flows for the Songwe sub-basin will be greatest during the rainy season. However, it is anticipated that the dramatic reduction in river flow would be at its peak in March 2037, when the discharge will be 44.84 m^3/sec, and in March 2027, when the discharge will be 48 m^3/sec, under RCP 8.5. (**Figure 10(b)** and **Figure 10(c)**). According to the RCA4 regional climate model, the extreme rise in river flow will reach its peak in February 2023, in April 2083 under RCP 4.5, and in November 2027 and November 2046 by the CCLM4 and RCA4 regional climate models, respectively. The management of the sub-basin's water resources,

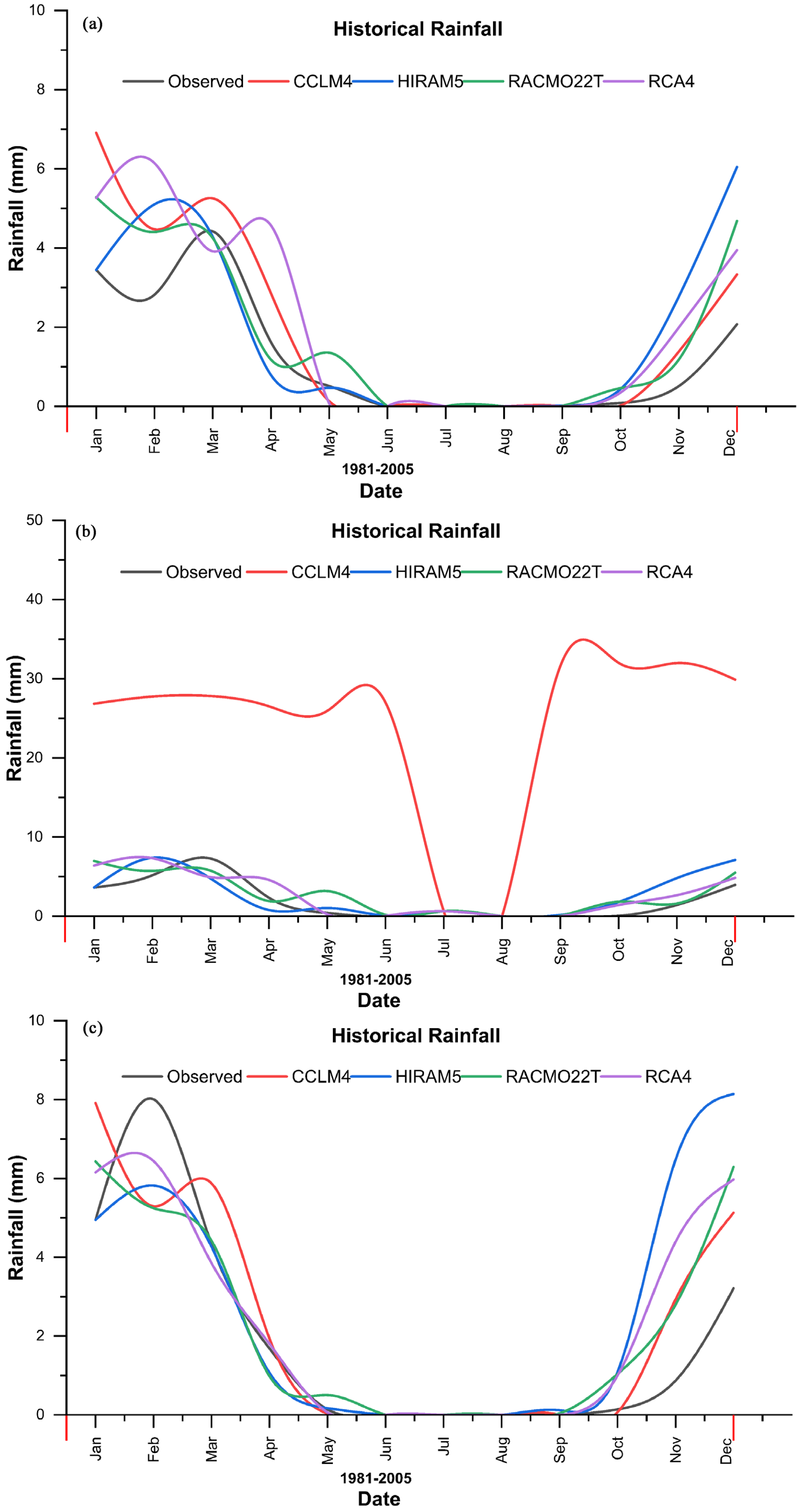


Figure 6. (a) Historical Monthly mean rainfall at Galula station (1981-2005); (b) Historical Monthly mean rainfall at Lupa station (1981-2005); (c) Historical Monthly mean rainfall at Mbeya maji station (1981-2005).

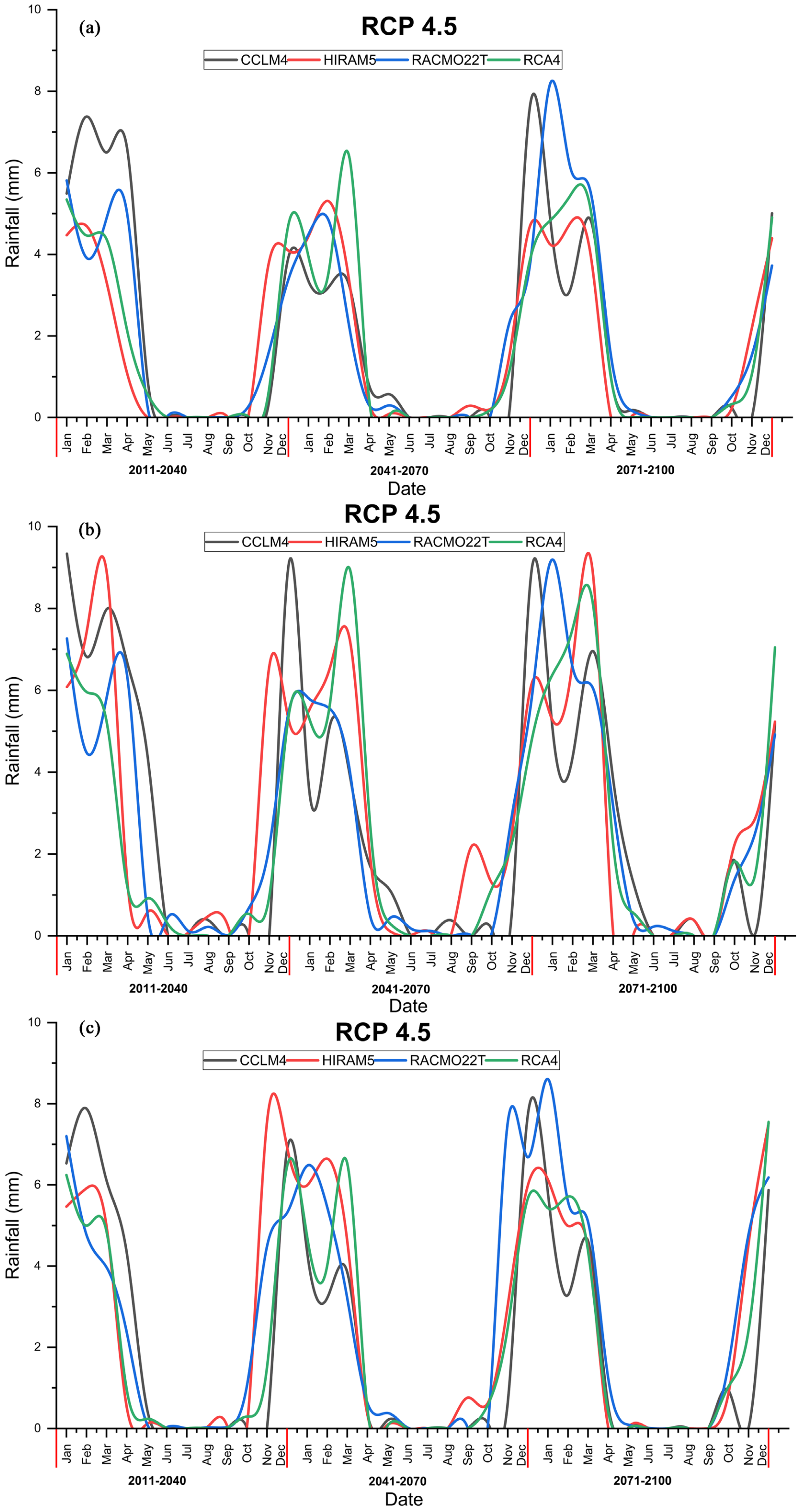


Figure 7. (a) Simulated Monthly mean raifall at Galula station (2011-2100) under RCP 4.5; (b) Simulated Monthly mean raifall at Lupa station (2011-2100) under RCP 4.5; (c) Simulated Monthly mean raifall at Mbeya maji station (2011-2100) under RCP 4.5.

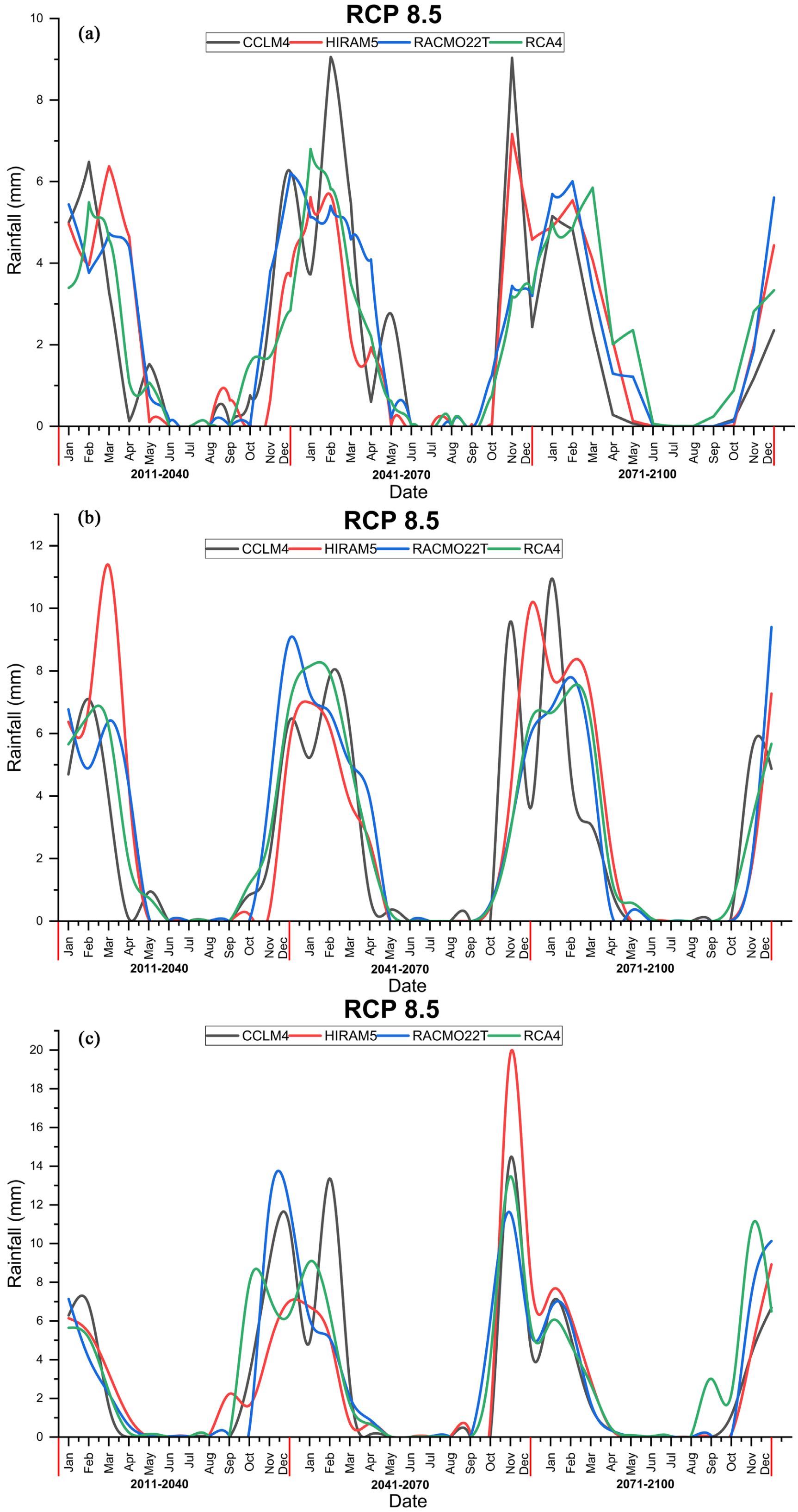
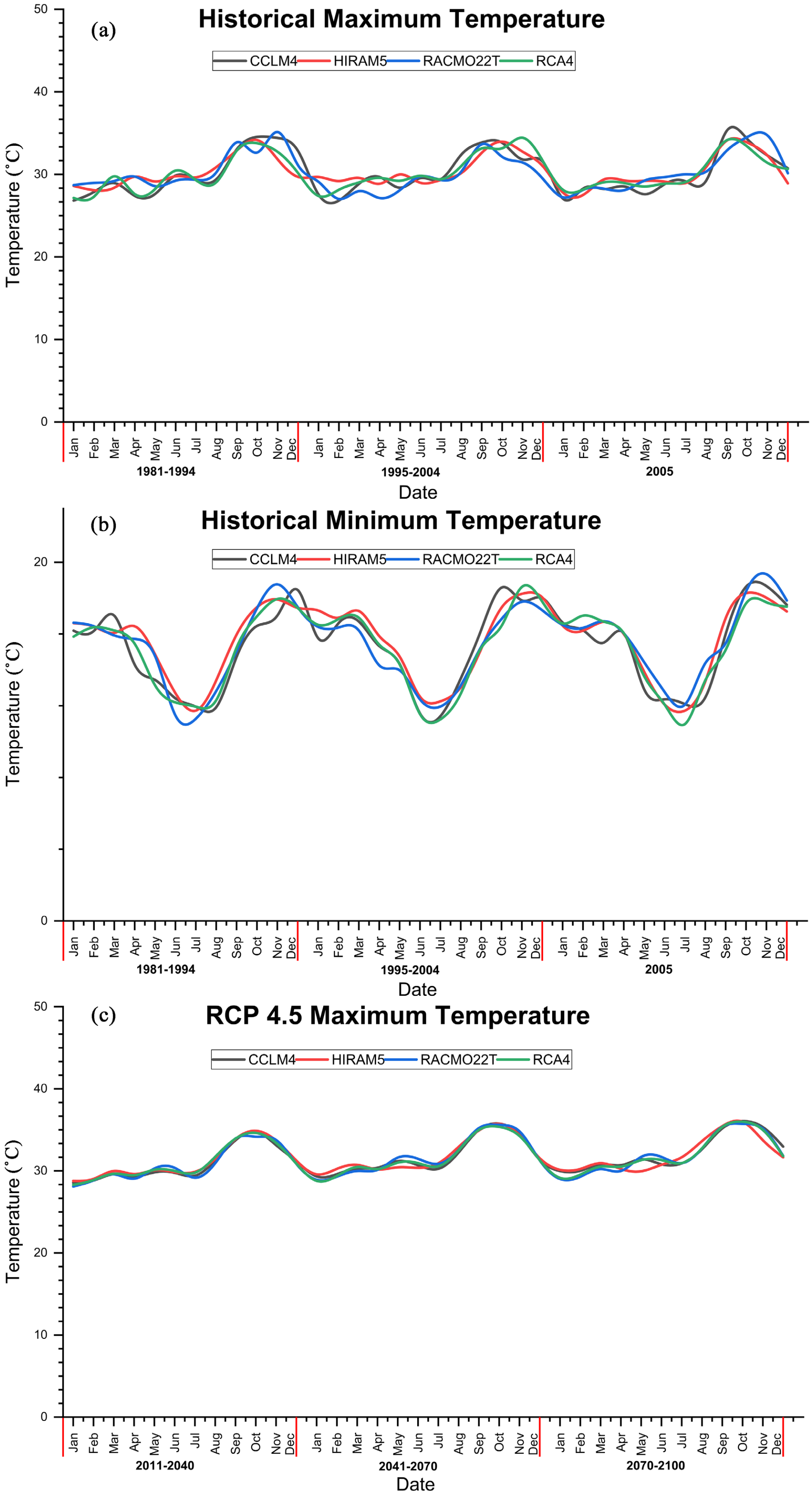


Figure 8. (a) Simulated Monthly mean raifall at Galula station (2011-2100) under RCP 8.5; (b) Simulated Monthly mean raifall at Lupa station (2011-2100) under RCP 8.5; (c) Simulated Monthly mean raifall at Mbeya maji station (2011-2100) under RCP 8.5.


(a)
Historical Maximum Temperature
CCLM4
HIRAM5
RACMO22T
RCA4
Temperature (˚C)
0
10
20
30
40
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
1981-1994
1995-2004
2005
Date
(b)
Historical Minimum Temperature
CCLM4
HIRAM5
RACMO22T
RCA4
Temperature (˚C)
0
20
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
1981-1994
1995-2004
2005
Date
(c)
RCP 4.5 Maximum Temperature
CCLM4
HIRAM5
RACMO22T
RCA4
Temperature (˚C)
0
10
20
30
40
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2011-2040
2041-2070
2070-2100
Date

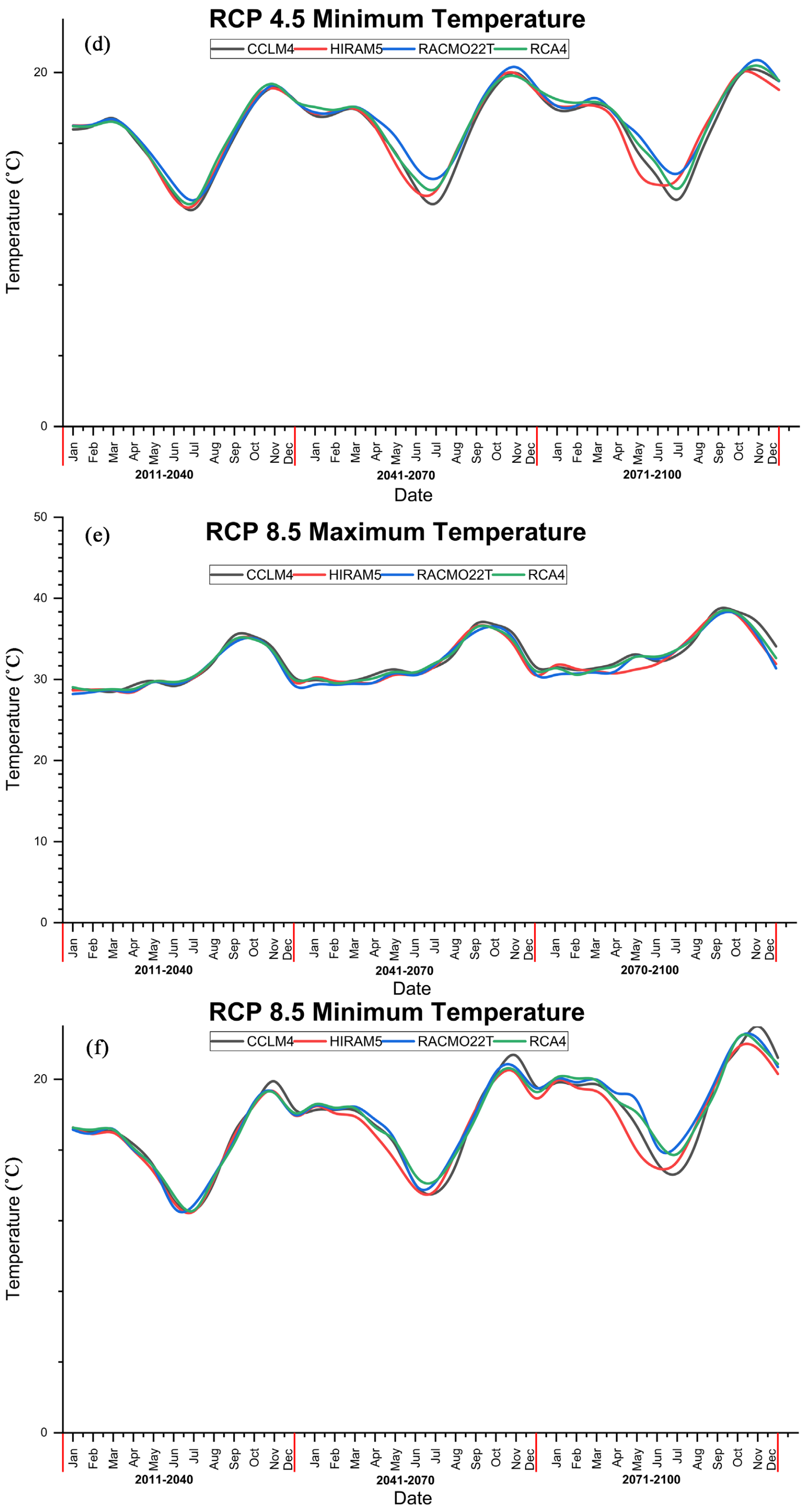
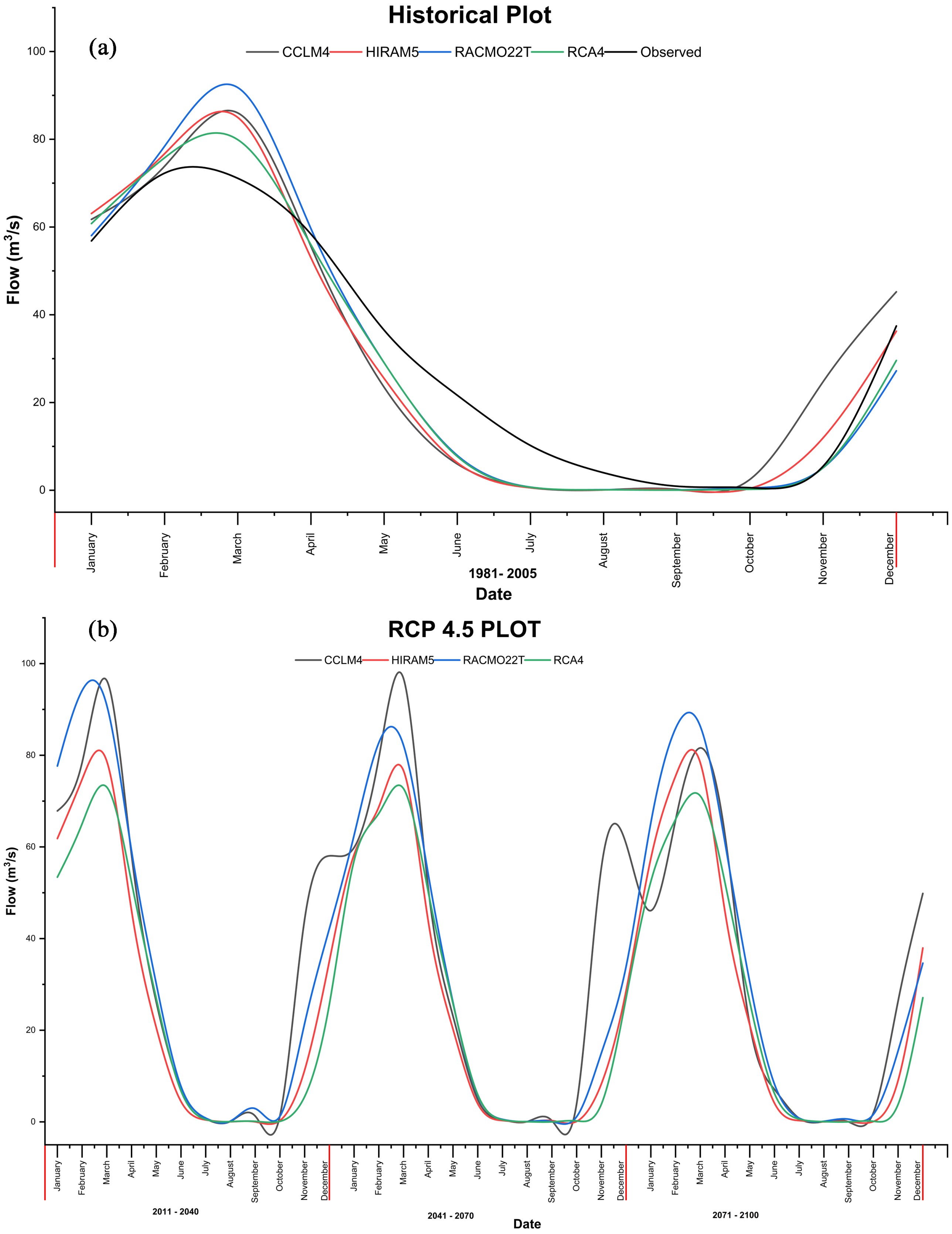


Figure 9. (a) Historical Monthly mean maximum temperature at Galula station; (b) Historical Monthly mean minimum temperature at Galula station; (c) Simulated Monthly mean maximum temperature at Galula station RCP 4.5; (d) Simulated Monthly mean minimum temperature at Galula station RCP 4.5; (e) Simulated Monthly mean maximum temperature at Galula station RCP 8.5; (f) Simulated Monthly mean minimum temperature at Galula station RCP 8.5.


(a)
Historical Plot
CCLM4
HIRAM5
RACMO22T
RCA4
Observed
Flow (m³/s)
0
20
40
60
80
100
January
February
March
April
May
June
July
August
September
October
November
December
1981- 2005
Date
(b)
RCP 4.5 PLOT
CCLM4
HIRAM5
RACMO22T
RCA4
Flow (m³/s)
0
20
40
60
80
100
January
February
March
April
May
June
July
August
September
October
November
December
2011 - 2040
2041 - 2070
2071 - 2100
Date

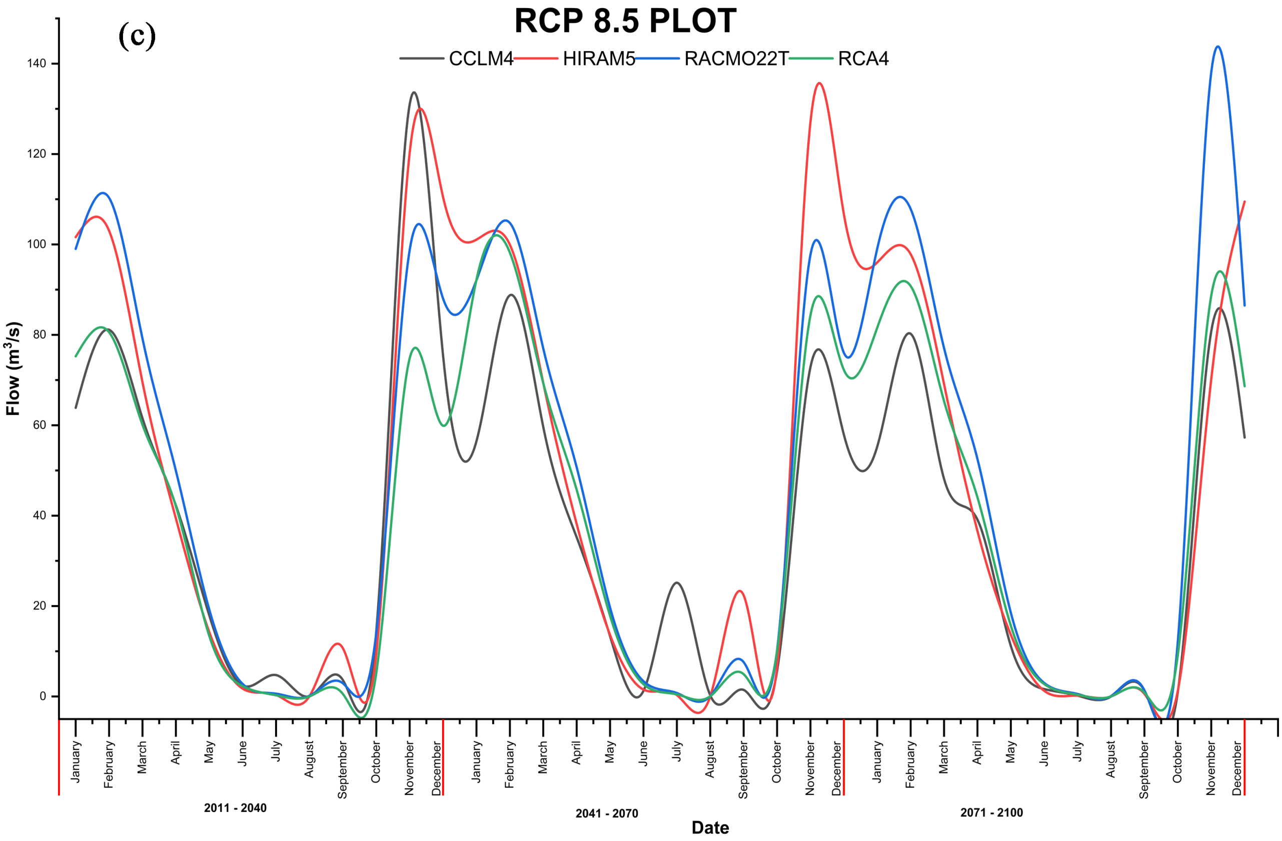


Figure 10. (a) Historical Monthly mean discharge at Galula station (1981-2005); (b) Simulated Monthly mean discharge under RCP 4.5 at Galula station (2011-2100); (c) Simulated Monthly mean discharge under RCP 8.5 at Galula station (2011-2100).

biodiversity, and hydraulic structures may be impacted by the anticipated reduction and rise in river flow throughout both the dry and wet seasons.

3.2.3. Climate Change Impacts on Water Components

The simulated average monthly stream flow for the two climate change scenarios was used to examine the effects of climate change on various water balance components. For the sub-basin, differences between the baseline and future period forecasts in the average annual precipitation, evaporation, surface runoff, lateral flow, groundwater, percolation, and total water yield were estimated. Early and mid-century annual precipitation increased by 67.6 mm under RCP 4.5, while annual precipitation decreased by 13.4 mm under RCP 4.5 for the CCLM4 regional climate model. These changes were observed in surface runoff, lateral flow, groundwater, total water yield, percolation, and evaporation (Table 5). According to RCP 4.5, the HIRAM5 regional climate model, annual precipitation decreased by 189.6 mm, as did surface runoff, lateral flow, groundwater, total water yield, percolation, and evaporation for each of the three time periods of the century (Table 6). For the RACMO22T regional climate model, the increase in annual precipitation, surface runoff, lateral flow, groundwater, total water yield, percolation, and evaporation for the early and end of the century and the decrease in annual precipitation, runoff, lateral flow, groundwater, total

Table 5. Simulated Water balance under CCLM4 RCM.

Hydrologic unit	Annual averages						
	Baseline (1981-2005)	Present century (2011-2040)		Mid-century (2041-2071)		End century (2071-2100)	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Precipitation (mm)	974	996.3	920.2	1064.6	868.3	960.6	853.7
Surface runoff (mm)	153.63	178.88	168.81	233.73	136.9	198.66	141.18
Lateral flow (mm)	13.17	13.51	12.94	13.45	12.08	11.98	11.22
Groundwater (mm)	14.94	15.4	13.48	15.68	12.43	13.08	12.08
Total water yield (mm)	432.4	466.21	416.45	525.77	361.38	436.07	355.65
Percolation (mm)	300.81	308.68	271.96	316.07	252.35	262.08	242.05
Evaporation (mm)	503.9	494.7	464.4	499.1	464.9	488.4	458.2

Table 6. Simulated Water balance under HIRAM5 RCM.

Hydrologic unit	Annual averages						
	Baseline (1981-2005)	Present century (2011-2040)		Mid-century (2041-2071)		End century (2071-2100)	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Precipitation (mm)	972.6	930.4	1014.1	906	1020.6	729.6	1025.6
Surface runoff (mm)	123.4	117.23	179.3	119.1	195.52	80.45	203.56
Lateral flow (mm)	13.69	13.02	16.19	12.43	15.77	11.53	14.78
Groundwater (mm)	15.51	14.55	16.91	13.88	16.6	9.1	16.09
Total water yield (mm)	418.88	390.91	501.87	377.69	509.37	239.18	504.38
Percolation (mm)	315.98	291.94	342.44	278.92	334.02	182.44	327.1
Evaporation (mm)	516.8	506.8	474.2	494.1	472.6	455.9	477.9

water yield, percolation, and evaporation for the middle of the century under RCP 4.5 (Table 7). The reduction in yearly precipitation, surface runoff, groundwater, total water yield, percolation, and evaporation under RCP 4.5, as well as the reduction in precipitation, lateral flow, groundwater, percolation, and evaporation for the middle of the century. Additionally, the RCA4 regional climate model predicts a decrease in lateral flow, percolation, and evaporation at the end of the century under RCP 4.5. (Table 8). HIRAM5, RACMO22T, and RAC4 regional climate models projected higher annual precipitation, surface runoff, lateral flow, groundwater, total water yield, and decreased evaporation and percolation for all time periods of the century under RCP 8.5 (Tables 6-8); however, the CCLM4 climate model projected lower annual precipitation, surface runoff, lateral flow, groundwater, total water yield, percolation, and evaporation under RCP 8.5 for (Table 5). Towards the end of future periods, a major change in both water balance components is anticipated as a result of the

Table 7. Simulated Water balance under RACMO22T RCM.

Hydrologic unit	Annual averages						
	Baseline (1981-2005)	Present century (2011-2040		Mid-century (2041-2071)		End century (2071-2100)	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Precipitation (mm)	974.4	996.9	999.1	955.4	1016	1017	1065.7
Surface runoff (mm)	76.56	68.9	97.21	64.46	97.58	76.01	116.6
Lateral flow (mm)	14.57	16.29	17.94	14.89	17.52	15.77	18.41
Groundwater (mm)	17.77	18.87	19.96	17.61	20	19.06	20.68
Total water yield (mm)	418.49	433.25	484.33	400.83	483.38	441.93	515.24
Percolation (mm)	358.2	378.52	403.66	354.85	402.01	384.44	417.32
Evaporation (mm)	522.2	531.4	478.1	519	497.2	538.9	511.2

Table 8. Simulated Water balance under RCA4 RCM.

Hydrologic unit	Annual averages						
	Baseline (1981-2005)	Present century (2011-2040)		Mid-century (2041-2071)		End century (2071-2100)	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Precipitation (mm)	974	953.2	973.2	971.5	985.3	990.5	1024.9
Surface runoff (mm)	70.51	69.18	99.41	78.24	100.6	84.28	117.7
Lateral flow (mm)	14.14	13.41	16.38	13.47	15.83	13.49	15.02
Groundwater (mm)	16.73	16.15	16.82	16.56	17.01	17.07	17.81
Total water yield (mm)	389.26	374.07	420.68	390.72	423.79	406.3	454.17
Percolation (mm)	366.76	324.07	340.1	333.42	344.06	343.3	360.06
Evaporation (mm)	550.2	545.1	515.1	544.5	522.6	547.4	529.9

changing climate.

4. Discussion

In the Songwe sub-basin, climate variability has had a significant impact on the hydrological processes. The decrease in river flow in the Songwe sub-basin and Lake Rukwa's water levels downstream are clear signs of the impacts of human activity and climate change [2]. The management of water resources and planning in this sub-basin are both projected to be impacted by climate change. The application of a hydrologic SWAT model and bias correction of the output from the four regional climate models used in the simulation is required for the assessment of how climate change would affect river flows. To get the most out of the bias correction of the output from the Regional Climate Models, observed meteorological data, as well as weather-generated data by SWAT in data-scarce areas, were necessary.

In places with a lack of data, the lack of long-term observations has a significant impact on studies of climate change. To enable regional climate change impact evaluations at regional scales, high-resolution climate model output is used [21]. To evaluate the effect of climate change on river flows in the Songwe sub-basin, we chose four regional climate models from the CORDEX-AFRICA. The model performances for temperature, precipitation, and hydrology were compared to previously recorded data. To determine the effect of climate change on river flows in the Songwe sub-basin, the regional climate models (RCMs) were bias-corrected using meteorological data that was observed and weather data that the SWAT model generated in the sub-basin. The bias-corrected RCM output was then used directly as input data in the calibrated SWAT model. The hydrological processes in the sub-basin may be impacted by the predicted increase in runoff during the early, middle, and end of the century under RCP 8.5 and a decrease in surface runoff under RCP 4.5. The RCP 8.5 scenario predicts that the flow will increase throughout the entire century. The conflict over the use of the water resource in the sub-basin is anticipated to significantly grow as a result of the simulated decrease in river flows during the dry season.

5. Conclusion

One of the major difficulties in managing the hydrological components in the Songwe sub-basin is the impact of climate change. In this investigation, we evaluate how climate change may affect river flows in the sub-basin. For the purpose of predicting precipitation, minimum and maximum temperatures, and river flows for historical and future periods of the century, four regional climate models, which produced their output under two different climate change scenarios, RCP 4.5 and RCP 8.5, were employed. The parameters established for the hydrologic evaluation of the reference period and estimated future river flows serve as the foundation for choosing the climate model. This project's objective was to use four regional climate models to analyze the effects of climate change on river flows in the Songwe sub-basin. In general, the majority of the scenarios suggest a drop in mean monthly precipitation and an increase in mean monthly temperature for the next century. There was little agreement in the scenarios' projections of the mean monthly rainfall, even though they all projected rising mean monthly temperatures and mean annual temperatures for the study periods. But for the three future eras, the mean annual rainfall was universally predicted to decline in all scenarios. The hydrological components of the sub-basin may be negatively influenced by climate change, according to SWAT model simulation results. Under the RCP 4.5 and RCP 8.5 scenarios compared to the baseline period, the annual precipitation, surface runoff, lateral flow, groundwater, and total water production may increase or decrease in evaporation and percolation for all periods early and mid-century. The relationship between temperature and evaporation was reciprocal, and the relationship between precipitation and temperature and other hydrological components was reciprocal as well. This implies that the sub-basin may see both a decline and an increase in water balance components in the ensuing century. Therefore, to lessen the detrimental effects of climate change on precipitation, temperature, and river flow in the Songwe sub-basin, proper adaptation, and mitigation methods should be put in place.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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