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Impacts of Climate Change on the Water Resources of Guder Catchment, Upper Blue Nile, Ethiopia

Fikru Fentaw[1*], Bahiru Mekuria[2], Abebe Arega[3]

[1] Department of Civil and Environmental Engineering, Kombolcha institute of Technology (Kiot), Wollo University, Kombolcha, Ethiopia
[2] School of Civil Engineering and Architecture, Adama Science and Technology University, Adama, Ethiopia
[3] Department Civil Engineering, institute of Technology, Hawasa University, Hawasa, Ethiopia

Email Address

fikrwn@gmail.com (Fikru Fentaw)
*Correspondence: fikrwn@gmail.com

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Abstract:

This study uses Climate Model outputs of HadCM3A2a and HadCM3B2a SRES climate scenarios and downscale the predictors into finer scale resolution using Statistical Downscaling Model (SDSM) to simulate and project the climate at local scale in order to investigate the hydrological impact of possible future climate change in Guder catchment, Upper Blue Nile Basin (Ethiopia). The results, obtained from this climate model, were compared to the observational datasets for precipitation and temperature for the period 1990-2008. To estimate the level of impact of climate change, climate change scenarios of precipitation and temperature were divided into time windows of 30 years each from 2011 to 2100.The downscaled A2a and B2a emission scenarios result indicates a significant increasing trend in mean temperature and precipitation in all future time periods in the study catchment. We applied the Soil and Water Assessment Tool (SWAT) to investigate the response of the water resources of the Guder River catchment to the scenarios of projected climate change. The model output shows that there may be an annual and seasonal increase in inflow volume for both A2a and B2a emission scenarios in three benchmark periods in the future. Potential evapotranspiration in the catchment will also increase up to 25%. Generally, results presented in this study can provide valuable insight to decision makers on the degree of vulnerability of Guder river catchment to climate change, which is important to design appropriate adaptation and mitigation strategies.

Keywords:

Guder Catchment, Water Resources, SWAT Model, Climate Change, SDSM, SRES

1. Introduction

Water is the most important natural resource required for the survival of all living species. Since the available amount of water is limited, scarce, and not spatially distributed in relation to the population needs, proper management of water resources is essential to satisfy the current demands as well as to maintain sustainability. Water resources planning and management in the 21st century is becoming difficult due to the conflicting demands from various stakeholder groups, increasing population, rapid urbanization, climate change producing shifts in hydrologic cycles, the use of high-yielding but toxic chemicals in various land use activities and the increasing incidences of natural disasters. Therefore, the impacts of climate change on water resources are the most crucial research agenda in worldwide level [1]. Scientists agreed that climate change have adverse impacts on socio-economic development of all nations. But the degree of the impact will vary across nations.

It is expected that changes in the earth's climate will hit developing countries like Ethiopia first and hardest because their economies are strongly dependent on crude forms of natural resources and their economic structure is less flexible to adjust to such drastic changes [2, 3, 4, 5, 6]. Numerous studies have been conducted in Ethiopia at different scales ranging from small watersheds to the entire country [7, 8, 9, 10, 11] to assess the impacts of climate change on hydrologic systems. Many studies have focused on the potential impacts of climate change on watershed hydrology including changes in precipitation, temperature, potential evapotranspiration, stream flow, and soil moisture in the upper Blue Nile basin [9, 11, 12, 13, 14, 15]. Climate change impacts on the upper Blue Nile Basin water resources have been investigated in different time periods by different researchers using outputs from General Circulation Models (GCMs) on different future climate scenarios and hydrologic models [6, 10, 13, 16, 17, 18].According to all the above listed studies the current climate variability is already imposing a significant challenge to Ethiopia especially areas in the Blue Nile Basin by affecting food security, water and energy supply, poverty reduction and sustainable development efforts, as well as by causing natural resource degradation and natural disasters. Therefore, assessing the impact of climate change on the water resource of Guder catchment, upper Blue Nile will be expected to have importance to be considered in development plans in water resources, agriculture and to overcome the impacts of intensifying recurrent droughts. This gives an opportunity to plan appropriate adaptation measures that must be taken ahead of time based on the projected climate change

In this study, we investigate the possible effects of climate change on water resources in Guder river catchment, Ethiopia by analyzing outputs from GCM and RCM models. Likely changes in runoff from the current baseline period until 2100 determined using output from GCMs forced with two IPCC SRES greenhouse gas emissions scenarios and downscale to catchment level using SDSM. The study investigated how changes in temperature and precipitation might translate into changes in stream flow and other hydrological components, using outputs from the selected climate scenarios. The physically based Soil and Water Assessment Tool (SWAT) model was used to determine the impact of climate change on the surface water resources availability in the Guder river watershed.

2. Material and Methods

2.1. Study Area Description and Datasets

2.1.1. Study Area Description

Guder Watershed, part of the Upper Blue Nile basin has a drainage area of 7, 011km^2 is situated in the Northwest of Ethiopia; in the South-eastern part of the Blue Nile Basin. This watershed geographically found in 7^{o}30' to 9^{o}30' N latitude and 37^{o}00' to 39^{o}00' E longitude. The topography of Guder catchment shown in **Figure 1** is complex mountainous areas and elevation ranging from 1500-3000m. Due to the topographic variations, the climate of the basin varies from cool (in the highlands) to moderately hot (in the relative lowland areas), with large variations in a limited elevation range. Mean annual temperature ranges from about 13^{0}C in the Mountains areas south of the towns of Ambo and Guder to around 28^{0}C in the moderately lowlands. The average annual rainfall also varies spatially and ranges from around 950mm in the lowland areas to more than 1450mm in the highlands of Mountains areas south of the towns of Ambo and Guder. Three main seasons characterize the study area: wet rainy season in summer locally known as "Kiremt" which lasts from June to September; the dry period, which extends between October and February and locally known as "Bega" and small rainy season in which most parts of the watershed receive considerable amount of rainfall which is locally known as "Belg" stays from March to May.

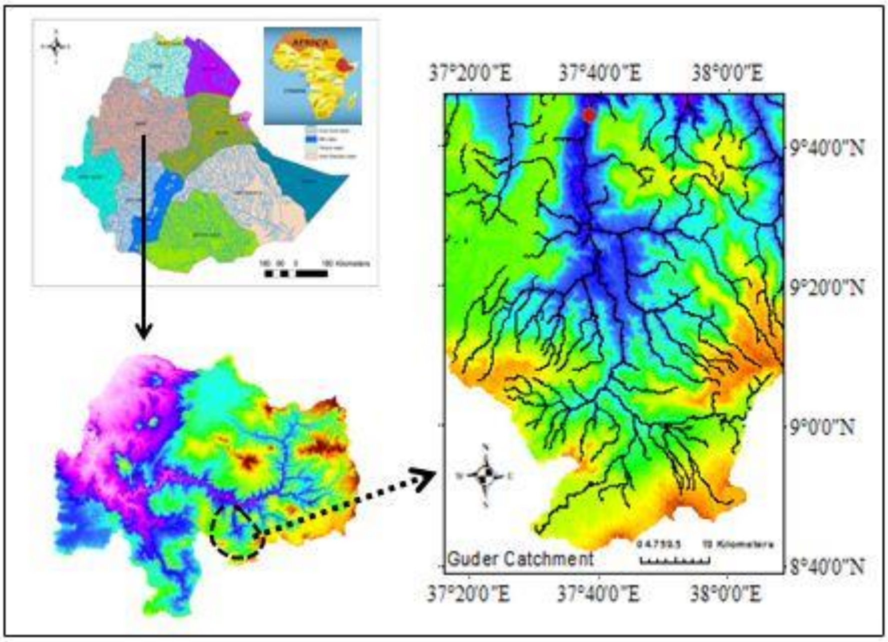

Figure 1. *Location of Guder catchment, Upper Blue Nile*

Corresponding to the variation in landscape and other soil forming factors such as climate and vegetation, the soils of the Guder sub-basin are also highly variable. The major soil types of Guder river watershed as per FAO [19] soil classification: Chromic Luvisols, Eutric Cambisols, Eutric Leptosols, Eutric Vertisols, Haplic Luvisols, Haplic Alisols and Haplic Nitisols. Apparently, these soils have various productivity limiting characteristics such as acidity, depth and permeability. The dominant land use of this catchment is rain-fed agriculture and cultivated lands in a various forms including intensively cultivated, cultivated land with scattered trees and shrubs and seasonally cultivated lands. In this basin agricultural land has expanded at the expense of natural vegetation, including forests, grazing land and shrub lands. Land use of the study area has changed over time due to over increasing population density, changing agricultural practices, urbanization and water related infrastructures.

2.1.2. Dataset

The basic datasets that are required by the hydrological model for climate change impact assessment are spatially distributed datasets (such as topographic, soil and land use data), climatic, stream flow and climate scenario data's.

Digital Elevation Model: The DEM is one of the essential inputs required by SWAT to delineate the watershed into a number of sub watersheds or sub basins. It is used to analyse the drainage pattern of the watershed, slope, stream network characteristics such as stream length and width of channel with in the watershed. The DEM used in this study was obtained from the Ministry of Water, Irrigation and Electricity of Ethiopia with a spatial resolution of 90m.

Soil and Land Use Data: Different types of soil texture and physical-chemical properties are required for SWAT simulations. The soil map obtained from Ethiopian Ministry of Water, Irrigation and Electricity GIS department; however, several properties like moisture bulk density, saturated hydraulic conductivity, percent clay content, percent silt content and percentage sand content of the soil which are required by SWAT model were not incorporated. These additional data were substantiated from FAO [19]. The source of land use map of the study is the Ethiopian Ministry of Water, Irrigation and Electricity and land use/land cover map was taken from the global Hydro1K dataset [20] and modified to correspond with the SWAT predefined land uses classification.

Climate Data: SWAT requires daily precipitation and minimum and maximum temperature climate data, which were obtained from the Ethiopian National Meteorological Service Agency near and within Guder river watershed for the period 1990- 2008, and were used as base line. The average percentage of missing data in the observed datasets was less than 8% and 5% of precipitation and temperature, respectively. Missing values were filled by the SWAT built-in weather generator developed by Nicks [21] that used a first-order Markov chain model.

Streamflow/ River Discharge Data: Daily river discharge data were obtained from Ministry of Ethiopian Water, Irrigation and Electricity hydrology department at Guder river catchment gauging stations. Observed flow data used for calibrating and validating SWAT model because it has the longest period data of the catchment from the year 1990-2005. The missing data values were replaced statistically by similar day averages for the previous years where there were existing data values. This approach was judge better than using weather generator imbedded in the model SWAT.

Climate scenario: The climate scenario data used for statistical downscaling model (SDSM) was obtained from the 20 ensemble GCM model output HadCM3A2a and HadCM3B2a scenarios two Special Report on Emissions Scenarios (SRES), which is produced by the greenhouse gas, sulphate aerosol, solar forcing and NCEP reanalysis data. The predictor variables are supplied on a grid by grid basis so that the data was downloaded from the nearest grid box (in African window 7.5^{o}N latitude and 37.5^{o}E longitude) as a zipped file to the study area. The predictor variables are supplied on a grid basis so that after selecting the Africa window and the location of Guder river catchment (at 37.5^{o}E longitude and 7.5^{o}N latitude) on the grids, the zip file will be available. The downloaded data's contain H3A2a and H3B2a (1961-2099) contains 139 years of daily GCM predictor data, derived from the HadCM3 A2 (a) and HadCM3 A2 (b) experiment, normalized over the 1961-1990 period. The reasons for

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selecting this HDCM3 GCMs were due to the fact that this model made daily predictor variables freely available to be directly fed into SDSM covering the study area with a better resolution. Additionally, they are the most used GCMs in previous studies such as [13, 18, 22, 23], and this model ranked first in performance evolution done by MAGICC/SCEGEN computer program tools. Moreover, they can represent two different scenario generations describing the amount of greenhouse gases (GHGs) in the atmosphere in the future. HadCM3 GCM used emission scenarios of A2 (separated world scenario) in which the CO_2 concentration projected to be 414ppm, 545ppm and 754ppm and B2 (the world of technological inequalities) where the CO_2 concentration to be expected 406ppm, 486ppm and 581ppm at the time period of 2020s, 2050s and 2080s respectively that were used in the CMIP3 for the IPCC's AR4 [1].

2.2. Statistical Downscaling Model (SDSM)

The Statistical Downscaling Model (SDSM) is best described as a hybrid of the stochastic weather generator and regression based in the family of transfer function methods. The stochastic component of SDSM enables the generation of multiple simulations with slightly different time series attributes, but the same overall statistical properties [24]. It requires two types of daily data, the first type corresponds to local predictands of interest (e.g. temperature, precipitation) and the second type corresponds to the data of large-scale predictors (NCEP and GCM) of a grid box closest to the station. The SDSM model categorizes the task of downscaling into a series of discrete processes such as quality control and data transformation, screening of predictor variables, model calibration and weather and scenario generation [24].

Screening potentially useful predictor-predictand relationships for model calibration is one of the most challenging but very crucial stages in the development of any statistical down scaling model. It is because of the fact that the selection of appropriate predictor variables largely determines the success of SDSM and also the character of the downscaled climate scenario [25]. After routine screening procedures, the predictor variables that provide physically sensible meaning in terms of their high explained variance, correlation coefficient (r) and the magnitude of their probability (p value) were selected. The model calibration process in SDSM was used to construct downscaled data based on multiple regression equations given daily weather data (predictand) and the selected predictor variables. The model was structured as monthly model for both daily precipitation and temperature downscaling. Consequently, twelve regression equations were developed for twelve months. Bias correction and variance inflation factor was adjusted until the model replicates the observed data. The weather generator helps to validate the calibrated model ideally using independent data. This operation generates the ensembles of synthetic daily weather data for the specified period with the help of regression model weights along with parameter file prepared during model calibration. To compare the observed and simulated data, SDSM has provided summary statistics function that summarizes the result of both the observed and simulated data. Time series of station data and large scale predictor variable information (NCEP reanalysis data) were divided into two groups; for the period from 1984-1995/ 1984- 2000 and 1996-2001/ 2001-2005 for model calibration and validation of HadCM3.

The Scenario Generator operation produces ensembles of synthetic daily weather series given observed daily atmospheric predictor variables supplied by a GCM either

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for current or future climate [24]. The scenario generation produced 20 ensemble members of synthetic weather data for 139 years (1961-2099) from HadCM3 A2a and B2a scenarios and for 95 years (2006-2100) from canESM2 for RCP2.6, 4.5 and 8.5 scenarios, and the mean of the ensemble members was calculated and used for further analysis. The generated scenario was divided into three time windows of 30 years of data (2011-2040), (2041-2070) and (2071-2100) henceforth called 2030s, 2050s and 2080s, respectively.

2.3. Hydrological Modeling (SWAT)

In this study, we used the Soil and Water Assessment Tool (SWAT) model a semi-distributed water assessment model [26], which has been applied widely in different regions across the world [31] and in the Upper Blue Nile Basin, Ethiopia [3, 9, 27, 28, 29] for climate change assessment applications. We select the SWAT model for this study mainly due to two reasons. Firstly, it has been successfully used for assessments of water cycling processes under different environmental conditions [30, 31]; and secondly, it has been successfully tested to simulate hydrological processes in the Upper Blue Nile basin [9, 10, 27, 29]. Hence, SWAT is a suitable hydrologic model to assess impacts of climate change on the water resources of Guder watershed part of the upper Blue Nile Basin.

In the SWAT-modeling approach a watershed is divided in to a number of sub-basins. Each sub-basin is then further divided into groups of similar soil- and land cover areas, because they are supposed to give similar hydrological responses, are called HRUs [28]. The SWAT-hydrological compartment in a watershed consists of a land phase and a water- routing phase. The land phase of the hydrologic cycle controls the amount of water, sediment and pesticide loadings to the main channel in each sub-basin, whereas the routing phase of the hydrologic cycle shows the movement of water, sediment, nutrients, etc., through the channel network of the water of the watershed and then to the outlet [28].

The land phase of the hydrologic cycle is described by the transient water balance equation applied to water movement through the soil, namely:

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

In which SWt is the final soil water content (mm), SWo is the initial soil water content on day i (mm), t is the time (days), Rday is the amount of precipitation on day i (mm), Qsurf is the amount of surface runoff on day i (mm), Ea is the amount of evapotranspiration on day i (mm), Wseep is the amount of water entering the vadose zone from the soil profile on day i (mm), and Qgw is the amount of return flow on day i (mm).

Surface runoff occurs, whenever the rate of water application to the ground surface exceeds the rate of infiltration, i.e. it is the excess water that cannot anymore infiltrate into the ground. Because of this process, the correct estimation of the infiltration is crucial for the subsequent evaluation of the surface runoff.

SWAT provides two infiltration methods for estimating the surface runoff volume component from HRUs, namely, the SCS-curve number (CN) method [32] or the Green & Ampt infiltration method [33]. Whereas the CN-method uses daily rainfall rates, the Green & Ampt technique requires smaller time-steps to properly simulate the infiltration process hence due to available observed data this study used SCS-curve number (CN) method.

Here the surface runoff is modeled in SWAT using the SCS curve number method, i.e.

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(P_{day} - I_a + 0S\right)} \quad (2)$$

Where, Qsurf is the accumulated runoff or rainfall excess (mm), Rday is the rainfall depth for the day (mm), and I_a is the initial abstraction which includes surface storage, interception and infiltration prior to run off (mm H_2O) and S is the retention parameter (mm H_2O).

The retention parameter is defined by Equation (3):

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad (3)$$

Where CN is the curve number for the day, which ranges from 0 to 100, depending on the soil perme major soil types ability, land use and the antecedent soil water conditions

The initial abstraction, I_a, is commonly approximated as 0.2S and equation (2) becomes

$$R_{surf} = \frac{\left(P_{day} - 0.2S\right)^2}{\left(P_{day} + 0.8S\right)} \quad (4)$$

We use the version of SWAT-2015 that works in ArcGIS Vesrion10.2. The study area was separated into 358 hydrological response units (HRUs) and 34 sub-basins within formation on topography, land use type, soil attributes, and management. We use the GLUE approach from the SWAT-CUP interface [34] to optimize parameters. As stated in equation (5, 6) Nash–Sutcliffe coefficient (E_{ns}) [35] and the coefficient of determination (R^2) were used to evaluate the goodness of the calibration and validation process.The optimal value to get best result is at E_{NS} and R^2=1. The calibration and validation processes were performed successfully, with values of E_{ns} and R^2 greater than 0.70 which simulates the streamflow well.

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}\left(Q_{o,i} - Q_{s,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{o,i} - \bar{Q}_o\right)^2} \quad (5)$$

$$r^2 = \frac{\left[\sum_{i=1}^{n}\left(Q_{o,i} - \bar{Q}_o\right)\left(Q_{s,i} - \bar{Q}_s\right)\right]^2}{\sum_{i=1}^{n}\left(Q_{o,i} - \bar{Q}_o\right)^2 \sum_{i=1}^{n}\left(Q_{s,i} - \bar{Q}_s\right)^2} \quad (6)$$

Where $Q_{o,i}$ is the i^{th} observation stream flow of i^{th} day , $Q_{s,i}$ is the i^{th} simulated stream flow of i^{th} day, Q_o^- is the mean of observed flow, Q_s^- is the mean of simulated flow and n is the total number of days

3. Results and Discussion

3.1. Climate Projection

For this research the climate scenario for future period was developed from statistical downscaling using the GCM predictor variables for the two SRES emission scenarios (HadCM3A2a and HadCM3B2a) for 90 years based on the mean of 20 ensembles and the analysis was done based on three 30-year periods centered on the 2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2099) representing the early, middle, and late of 21st century with reference to the present day, 1980s (1976–2005).

Temprature Change: Projected spatial distributions of average temperature anomaly considering the SRES HadCM3A2a and HadCM3B2a climate scenarios derived from the SDSM downscaled GCMs and RCMs over Guder river catchment for the three future time period (i.e., 2020s, 2050s and 2080s) are presented in **Figures 2**. The overall analysis (2011-2099) of temperature showed that there may be increasing trends in both emission scenarios (A2a and B2a). The average annual change in temperature in 2020s will be increased by 1.55°C and 1.45°C for A2a and B2a emission scenarios, respectively. For the 2050s periods the average annual change temperature will be increased by 2.76°C and 2.63°C for A2a and B2a emission scenarios, respectively. Also for the period of the 2080s the average change in annual temperature will be increased from 4.22°C and 3.94°C for A2a and B2a emission scenarios, respectively. Increasing maximum temperature showed more variation at the monthly time step with arrange from 0.8°C to 2.2°C in 2020s, 2.1°C to 3.9°C in 2050s and 2.9°C to 5.1°C in 2080s for both A2a and B2a emissions scenarios.

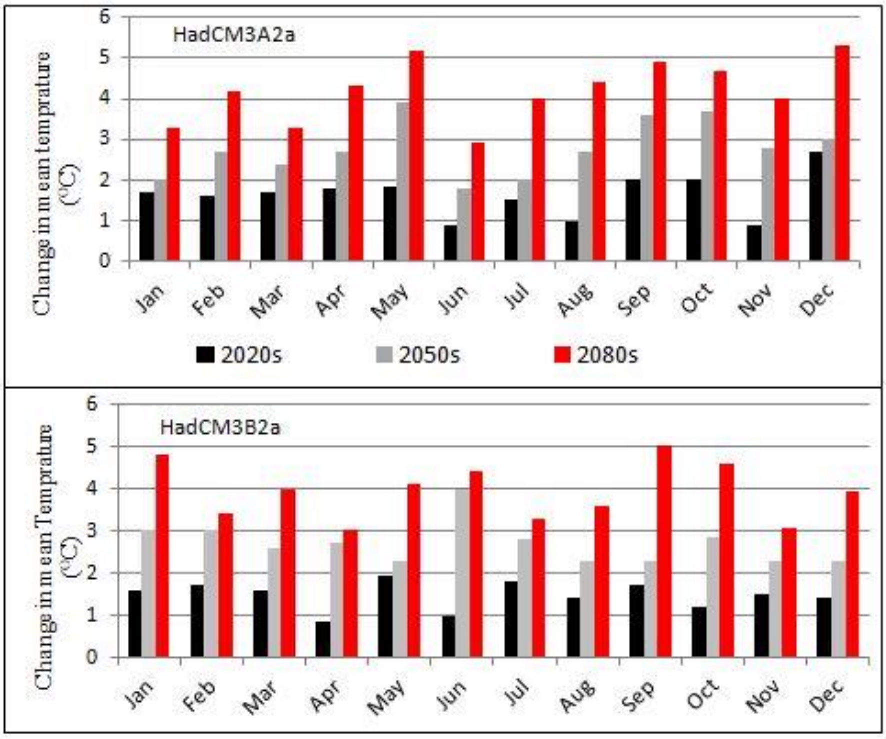

Figure 2. *Change mean monthly temperature at Guder catchment for both scenarios*

Precipitation Change: precipitation projection exhibited an increase in average mean precipitation in periods (2020s, 2050s and 2080s). **Figure 3** indicates that there may be a decreased in precipitation for months September & October and increase in all other months for both emission scenarios (A2a and B2a). The overall effect in 2020s may be an increase of average annual precipitation by 15.35% in the A2a scenario and 18.11% in the B2a scenario. In 2020s, the maximum monthly average precipitation observed in December which would increase up to 3.06% & 4.87% in both A2a & B2a emission scenarios respectively. The overall effect in 2050s may be an increase of average annual precipitation by 18.07% in the A2a scenario and 23.995% in the B2a scenario. In 2050s, the increase in monthly average precipitation may reach up to 5.37% for December in the A2a scenario and 7.7% for November in the B2a scenario. In 2080s the A2a and B2a scenarios showed an increase in average annual precipitation amount by 16.41% and 23.06% respectively. In the 2080s, the decrease in monthly average precipitation may reach up to 2.0% for October in the A2a scenario and 3.23% for September in the B2a scenario.

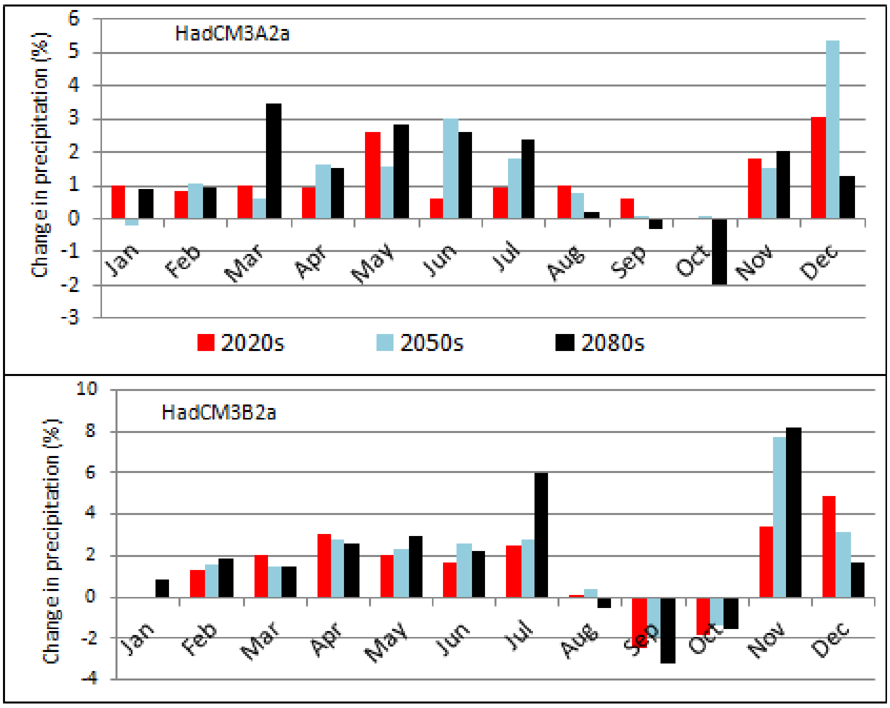

Figure 3. *Percentage change of precipitation at Guder catchment in both scenarios*

3.2. Stream Flow Analysis Results

This study indicates that the SWAT hydrological model can be an effective tool for accurately simulating the hydrology of the Guder catchment. Daily statistics computed for the calibration and validation periods show strong correlations between the simulated and observed streamflow as the Coefficient of determination (R^2) and Nash-Sutcliffe efficiency **(**E_{NS}) were greater than 0.7 and in both the calibration and validation periods. The trends of monthly, seasonal and annual future streamflow projection are described below.

In the 2020s for the A2a scenario, the flow volume may show an increase for all the months. In this period an increase up to 55% in monthly flow volume may be expected. Increase in flow volume may be observed in months which showed an increase in monthly precipitation. In the 2020s for B2a scenario shown in **Figure 4**, the same effect as the A2a scenario of 2020s may be observed. In 2050s for both A2a & B2a scenarios, the increase in precipitation is reflected in an increase in flow volume. For A2a scenario the monthly variation of change in streamflow is between 5%

and 49%. And also for B2a varies in 2% and 57%. In 2080s for the A2a and B2a emissions scenarios an increase in flow volume observed in all months. For A2a scenario the monthly variation of change in streamflow volume is between 2% and 58% and also for B2a variation in between 4% and 59%.

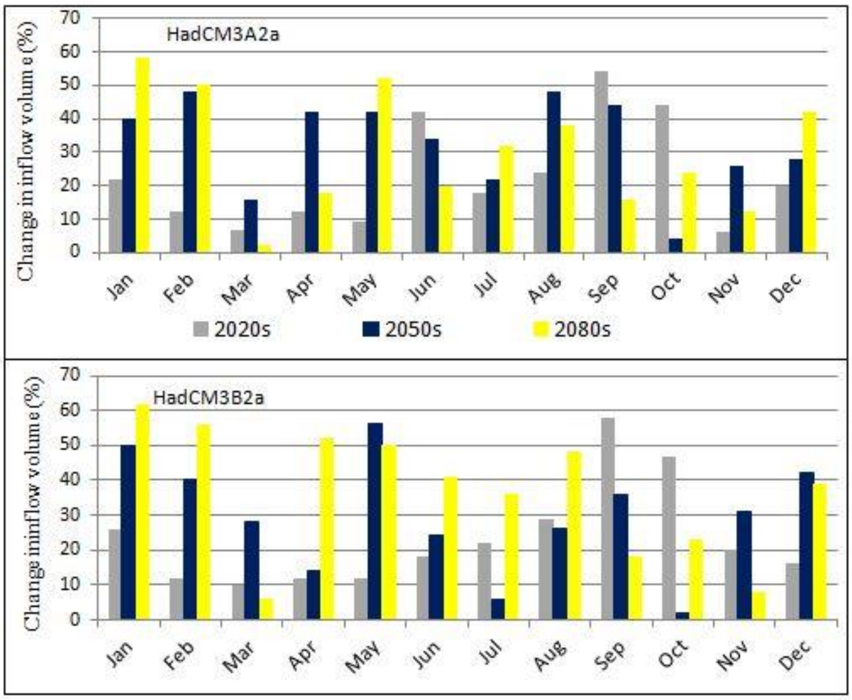

Figure 4. *Monthly percentage change in flow volume for both A2a and B2a scenarios in all time periods*

In the Guder catchment shown in **Table 1**, there would be a change seasonal; *Kiremt* (June to September), *Belg* (March to May), and *Bega* (October to February) flow volume for both A2a and B2a scenarios. There might be also average annual increase in flow volume for the next 90 years. For both A2a and B2a scenarios, there may be average annual increase in flow volume for the next 90 years up to 35%. *Kiremt* season flow volume may increase from ranges 28% to 35% and 19% to 31% for the both A2a and B2a scenarios, respectively. *Bega* season both scenarios show that there might be an increase in flow volume up to 52%. Also in *Belg* the flow volume may increases for both scenarios up to 41%.

Table 1. *Seasonal and annual flow percentage changes in Guder catchment for both SRES HadCM3 A2a and HadCM3 B2a climate scenarios*

Period	Kiremt	Bega	Belg	Annual
SRES A2a scenario				
2020s	28	19	10	23
2050s	35	38	34	33
2080s	30	51	24	35
SRES B2a scenario				
2020s	31	18	11	26
2050s	19	44	41	32
2080s	31	52	22	30

3.3. Sensitivity of Evapotranspiration to Climate Change

The simulations for the Guder catchment suggest that annual estimates of potential evapotranspiration are predicted to increase with increase in temperature. The projected on average annual increase in potential evapotranspiration is 3 - 15% for the 2020s and 7 - 25% for the 2050s and 2080s for both A2a and B2a emissions scenarios with respect to the baseline period (1990-2000). The monthly potential evapotranspiration (**Figure 5**) is high from June through September for both emission scenarios. But from January to March and December evapotranspiration showed a decreasing trend in the 2050s for both scenarios.

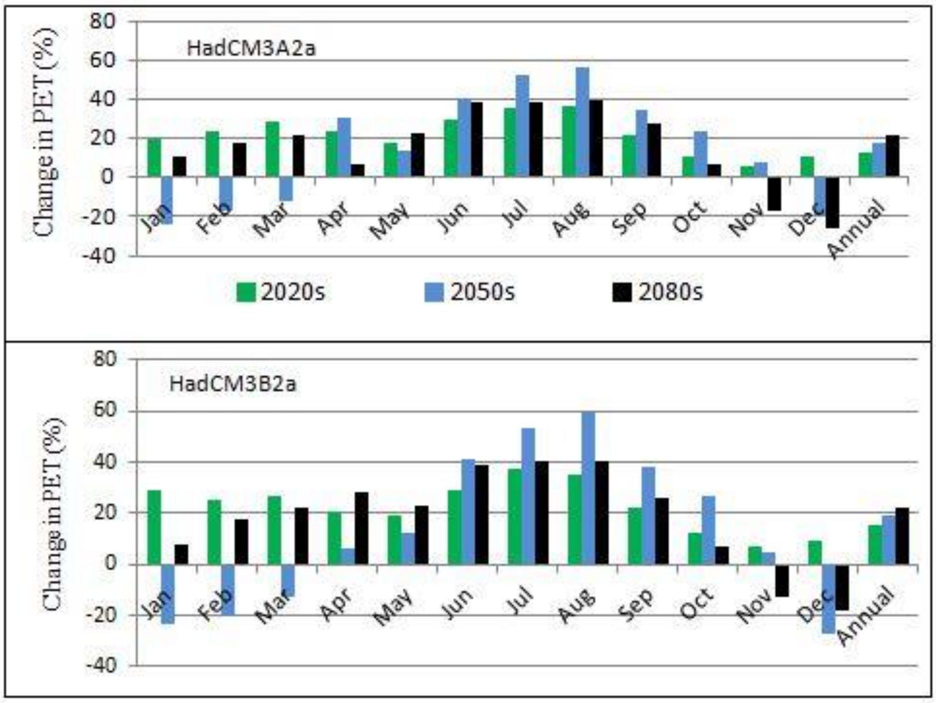

Figure 5. *Percentage change in monthly and annual Potential Evapotranspiration at Guder catchment*

4. Conclusions

This article presents an assessment of the expected future changes in the characteristics of precipitation and temperature over Guder catchment, upper Blue Nile considering 20 ensembles of GCM out puts of HadCM3 SRES A2a and B2a emissions scenarios with Statistical Downscaling (SDSM) modeling approach, and a complex physically based semi distributed hydrologic model (SWAT). The projection of temperature indicated that an increasing trend ranging from 0.13℃/decade to 5℃/decade for all areas of Guder catchment with a high confidence level. Meanwhile, the projected trends for precipitation showed an increasing trend throughout the studied area ranging from 11.5 to 25 percent in all time periods. The scenarios presented in this article highlighted the expected changes in precipitation and temperature patterns over the coming years indicating future impacts of climate change over Guder catchment.

Climate change impact on flow volume of Guder River was analyzed on a monthly, seasonal and annual basis. For both A2a and B2a emission scenarios, there may be an average annual increase in flow volume for the next 90 years up to 35%. And also all seasons show an increase in flow volume for both scenarios. The projected increase in annual Potential Evapotranspiration in the sub-basin will vary on annual average from

3 - 15% for the 2020s and 7 - 25% for the 2050s and 2080s for both A2a and B2a emissions scenarios. Overall, while the magnitude of the changes of streamflow and evapotranspiration can vary, impacts of climate change of water resources projects in the Guder catchment needs to be taken in to account for future water resources planning.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Acknowledgments

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