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Assessing Climate Change Impact on Gilgel Abbay and Gumara Watershed Hydrology, the Upper Blue Nile Basin, Ethiopia

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ABSTRACT

Climate change and variability have significant influences on hydrological cycles and the availability of water in the Horn of Africa. Projections of six General Circulation Models (GCMs) in association with high (A2) and low (B1) emission scenarios were adopted in this study from the Special Report on Emission Scenarios (SRES) for the period 2020 - 2039 to assess the impacts of climate changes on the Gilgel Abbay and Gumara watershed hydrology, the upper Blue Nile basin, Ethiopia. The GCMs selected were screened in accordance with baseline climate statistics of study areas. A weather generator was employed to generate daily temperature and precipitation to drive the General Water Loading Function (GWLF) hydrological model for simulating runoffs. Projected changes in temperature differences and precipitation ratios relative to the baseline were analyzed to explain the variations in evapotranspiration and the influences on runoff. Despite the fact that the projected magnitude varies among GCMs, increasing runoff in both wet and dry seasons was observed for both watersheds, attributable mainly to the increase in precipitation projected by most GCMs. In contrast to the great increases in runoff, variations in evapotranspiration are less significant. The projected runoff in both watersheds implies increased potential for promoting agricultural irrigation in the dry season. Furthermore, it would allow greater inflow to Lake Tana, the largest contributor to the Ethiopian Renaissance Dam on the Blue Nile. Therefore, concerned local, state, and federal government organizations shall be prepared to harness opportunities from the projected increase in runoff.

Key words: Climate change, Hydrological cycle, Gilgel Abbay and Gumara watersheds, GWLF, Runoff

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1. INTRODUCTION

The impact of climate change has been recognized with increased impacts overtime (IPCC 2001, 2007, 2014). The 100-year linear trend over the period 1906 - 2005 shows an average increase of 0.74°C in global mean temperature (IPCC 2007). The change in mean and variability of temperature and precipitation affects both natural and human systems in many ways (IPCC 2014). Fresh water resources, which are vital to all sectors and regions, are also prone to such direct effects. However, vulnerabilities to climate change vary regionally (Falloon and Betts 2006). East African countries are particularly likely to experience adverse impacts from climate change due to their topographical settings and poor adaptation capacity (Shemsanga et al. 2010; Mbaye et al. 2015). The economies of these countries depend heavily on rain-fed livestock agriculture (Schreck and Semazzi 2004; IPCC 2007; UNECA 2011; Enyew et al. 2014). For instance, about 83% of the population in Ethiopia depends on rain-fed agriculture with major activities relying on the rainy season (June to September) that accounts for 70 - 90% of the annual precipitation (Berhane et al. 2014; Enyew et al. 2014). Any extreme change, either positively or negatively, on the hydrological and meteorological variables will have great potential to affect regional water resources. Hence, there is an imperious need to quantify the impact of climate change on water resources to support building adaption measures to mitigate the impacts of climate change.

Many studies have focused on the potential impacts of climate change on watershed hydrology including changes

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in precipitation, temperature, potential evapotranspiration, stream flow, and soil moisture (Setegn et al. 2011; Dile et al. 2013; Tung et al. 2014; Musau et al. 2015). Variations in precipitation have direct effects on runoff, groundwater storage, frequency and intensity of floods, soil moisture, water supplies for irrigation, and hydroelectric power generation (Li et al. 2009; Tshimanga and Hughes 2012). Elevated temperature enhances evapotranspiration resulting in lowered soil moisture, increased crop water requirement, and declined stream flow (Enyew et al. 2014; Kusangaya et al. 2014). Beyene et al. (2010) concluded that stream flows from the Nile river basin will increase in 2020 - 2039 and decline in both 2040 - 2069 and 2070 - 2100 time windows based upon Special Report on Emission Scenarios (SRES) AR4. Setegn et al.'s (2011) results showed an increase in temperature for the Lake Tana Basin projected by all General Circulation Models (GCMs) with B1, A1B, and A2 emission scenarios for all time windows. Uncertainties in climate projections are the main reason causing diverse conclusions for precipitations trends in the Lake Tana basin region. Enyew et al. (2014) assessed the impact of climate change on hydrological drought in the Lake Tana basin for two future periods under A2 emission scenarios and found an increase trend in temperature, no trend in precipitation and increased stream flow for all rivers except the Gilgel Abbay watershed. The summer precipitation over the intermediate future period changes by 2.6 and 5.7% as projected by CNCM3 and IPSL GCMs respectively, while a reduction by 5.8% was given by European Centre for medium-range weather forecasts with HAMburg parameterization pachage (ECHAM) GCM projection. Abdo et al. (2009) assessed the impact of climate change on the hydrological cycle of the Gilgel Abbay watershed using the Hydrologiska Byrâns Vattenbalansavdelning Model (HBV) hydrological model and found that precipitation does not manifest a systematic increase or decrease in all future time windows unlike the minimum and maximum temperatures and related evaporations. However, significant changes and variations in seasonal and monthly flows are to be expected for the 2080s the runoff volume in the wet season will be reduced by approximately 11.6 and 10.1% for the A2 and B2 emission scenarios, respectively.

Most studies concluded that the Lake Tana basin, the upper Blue Nile in Ethiopia is highly sensitive to climate change. Combinations of Gilgel Abbay and Gumara watersheds account for more than half of the entire basin area and contribute the major amount of inflows into the lake. Although the significance of these two watersheds to the lake is large, climate impact studies are few at the watershed level for this basin. This study intends to assesses the potential impact of climate change on the hydrology of both the Gilgel Abbay and Gumara watersheds. Impact assessments will be focused on watershed level differences in changes of hydrological components for both watersheds. Historical data for daily precipitation and temperature from meteorological stations were collected and analyzed to provide baseline climatology. A weather generator was employed to generate daily temperature and precipitation simulations based on A2 and B1 emission scenarios in combination with the outputs from 6 GCMs to drive the GWLF (General Water Loading Function; Haith et al. 1992) hydrological model to simulate future runoffs. The rest of this paper is organized as follows: section 2 presents the research material and methods, section 3 presents results and discussion, and section 4 presents conclusions.

2. MATERIAL AND METHODS

2.1 Study Area

Lake Tana is the largest lake in Ethiopia and the third largest lake in the Nile basin countries with a lake area of 3041 km^2 and a maximum water depth of 14 m. The Tana basin with a total area of 15100 km^2 has national and regional significance. At the national level, it has great potential for irrigation, hydroelectric power generation, crop production, livestock production, and ecotourism. At the regional level, the lake is the head of the Blue Nile River, which contributes 80 - 85% of the inflow to the Nile River (Easton et al. 2010). The lake is the water tower of the Ethiopia's Grand Renaissance Dam on the Blue Nile.

The Lake Tana basin location is shown in Fig. 1. The central blue region is the Lake Tana. The colored region shows the Gilgel Abbay and Gumara watersheds with elevations to be investigated in this study. The Gilgel Abbay watershed is located south of Lake Tana with elevations from 1791 - 3510 m (masl). The Gumara watershed is located east of Lake Tana with elevations from 1791 - 3701 m mean above sea level. Four major watersheds contribute 93% of the inflow to Lake Tana (Kebede et al. 2006; SMEC 2008). The Gilgel Abbay and Gumara watersheds provide more than 65% of the inflow and cover more than 52.5% of the total catchment area. Since both watersheds contribute greater inflow to Lake Tana, fluctuations in their inflows due to climate change will have significant influences on the lake water balance. In addition to their inflow contribution, the Gilgel Abbay and Gumara watersheds are also the home of nearly 2 million people (FDREPC 2007) that depend entirely on subsistence rain-fed agricultural activities. Both watersheds have relatively large areas suitable for irrigation compared to the other watersheds in the Tana basin (Wale et al. 2013). The Gigel Abbay has a total catchment area of 455780 hectares while the Gumara has 176838 hectares. The Gigel Abbay has 54894 suitable for land irrigation while the Gumara has 24580 hectares.

The climate of the basin is dominated by ITCZ (Inter Tropical Convergence Zone) which is largely influenced by El Niño and the Indian Ocean dipole during some seasons. The main rain season is from June to September, which accounts 70 - 90% of the annual rainfall. The dry season is

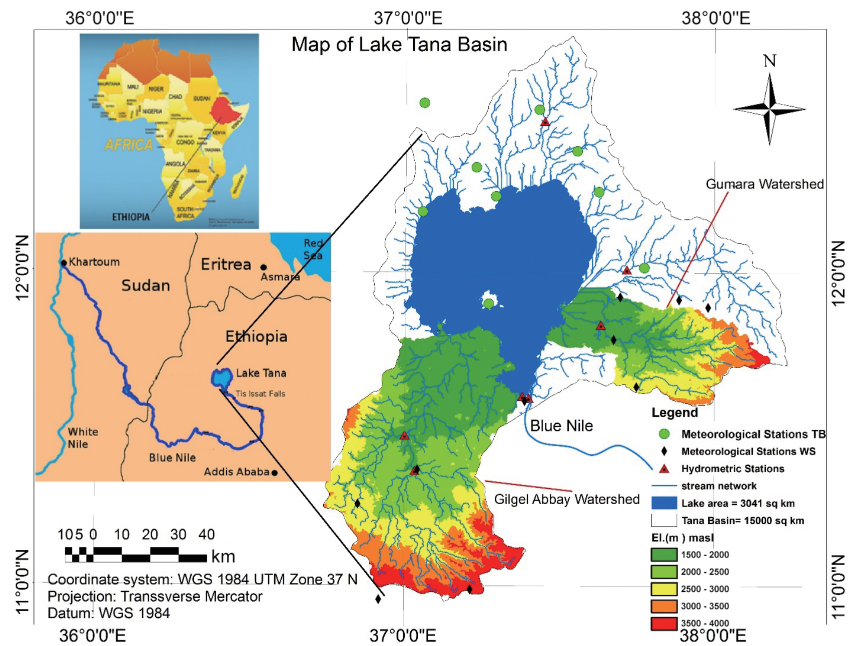

Fig. 1. Location of study area, hydrometric and metrological stations and stream network of Tana basin. (Color online only)

from October to May, accounting for 30 - 10% of the annual rainfall. There is an increasing trend in the rainfall magnitude when we move from the western part of the basin (e.g., Delgi) station 816 mm yr^{-1} (1983 - 2012) to the south end of the basin (e.g., Sekela) 1660 mm yr^{-1}. The mean annual rainfall ranges from 1406 - 1962 mm (1983 - 2012) in Gilgel Abbay and 1141 - 1515 mm (1983 - 2012) in the Gumara watershed.

There is high diurnal variation in daily temperature. The annual mean daily minimum and maximum temperature at Dangila (1993 - 2012) is 9.1 and 25.1°C, respectively, in the Gilgel Abbay watershed and 9.5 and 21.8°C, respectively, at Debre Tabor in the Gumara watersheds. The average daily mean annual temperature at Dangila weather station (1983 - 2012) is 17.2°C in Gilgel Abbay watershed and 15.7°C at Debre Tabor weather station in Gumara watershed.

2.2 Methodology

2.2.1 Data

Daily rainfall and temperature from 30 years data (1983 - 2012) from 10 metrological stations and 30 years of river discharge were collected from the National Metrological Agency (NMA) and Ministry of Water, Irrigation, and Energy (MoWIE). A Land Sat Image with a resolution of 90 by 90 m was used to delineate the watershed and prepare the land use/cover basin map using Arc GIS 10.1.

2.2.2 Conceptual Framework of the Study

The climate change impact on the Gilgel Abbay and Gumara watershed hydrology for a future period 2020 - 2039 under A2 and B1 from the Special Report on Emission Scenario (SRES) of the IPCC Fourth Assessment Report (AR4) was studied by considering 1980 - 1999 as a control period. The assessment methodology framework is depicted in Fig. 2. Twenty years of daily meteorological data were collected. Monthly precipitation ratios and temperature differences projected with A2 and B1 emission scenarios from the nearest 6 GCMs were taken. Two hundred samples of 1-year daily data were generated using a weather generator model for the baseline and projected weather data. The generated daily weather data was used to drive the calibrated hydrological model and simulate baseline and future runoff. The impact assessment was performed by comparing baseline and projected runoffs obtained in the previous step.

2.2.3 Climate Change Scenarios

2.2.3.1 Selection of GCMs and Scenarios

A total of 10 GCMs, including MPEH5, MIMR, MRCGCM, CSMK3, GFCM21, GFCM20, HADCM3, INCM3, NCCCSM, and IPCM4, were evaluated based on whether the local precipitation and temperature climatology can be captured with GCM baseline simulations. The coefficient of determination between the monthly precipitation (temperature) and GCM baseline simulations of monthly precipitation (temperature) was examined. The GCM skills on bassline precipitation are considered primarily as runoff is mainly affected by precipitation. The month having peak precipitation and temperature in GCMs baseline simulations was also examined to prevent bias peak runoff. For

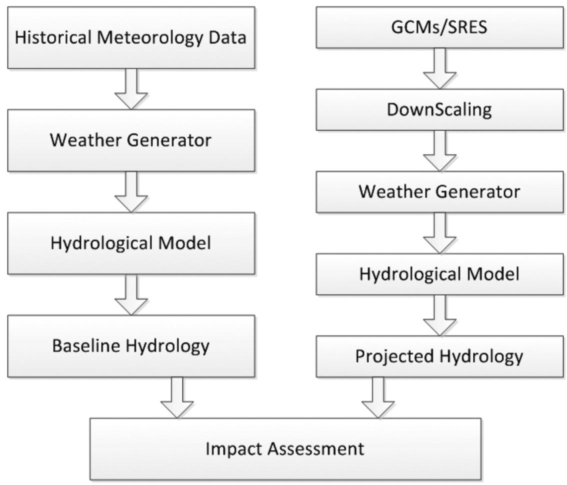

Fig. 2. Framework of the assessment methodology.

example, peak HADCM3 precipitation occurs in July while MPEH5 agrees with the climatology in August. HaDCM3 was not considered in this study. As a result, a total of 6 GCMs, including MPEH5, CSMK3, GFCM21, GFCM20, INCM3, and IPCM4, out of 10 GCMs evaluated were selected in this study.

Out of four base scenarios (i.e., A1, A2, B1, and B2) given in the IPCC SRES (IPCC 2007), both A2 and B1 scenarios were taken for this climate change impact study. The A2 scenario described as a world of independently operating, self-reliant nations and self-preservations of local identities with continuously increasing populations. B1 scenarios describe the world as more integrated and ecologically friendly with a global population that peaks in the mid-century and declines thereafter. This B1 world experiences rapid changes in economic structure towards service and information. The B1 scenarios are of a world more integrated and ecologically friendly, while the A2 scenarios are of a more divided world. Selections of A2 and B1 are used to represent the two most contrary emission pathways to provide possible upper and lower bounds of climate change impact. To reduce numbers of likely combinations, including different GCMs and scenarios, we tentatively selected A2 and B1 with contrasting descriptions for assessment in this study. Note that the SRES scenarios do not encompass the full range of possible futures which means that emissions may change less than the scenarios imply, or they could change more (Karl et al. 2009). This study used climate change scenario projected data for the short-term period (2020 - 2039). Comparisons are examined with precipitation and temperature change projections from 6 GCMs for both wet and dry seasons.

2.2.3.2 Downscaling

GCMs provide projections for future climate at large spatial scale, which is uncertain for impact assessment at the local scale, such as the watershed scale. Future river flow assessment requires daily precipitation and temperature at a watershed scale; therefore, there is a need to translate GCM outputs into daily precipitation and temperature series at the watershed scale for investigating the hydrological impact of climate change. A simple downscaling approach (i.e., considering the changes between the baseline and the future climate projected at the nearest GCMs grid to be adopted as the changes at the local grid) is directly employed to model changes in the Gilgel Abbay and Gumara watersheds as applied in Li et al. (2009) and Tung et al. (2014). The ratio of changes in monthly precipitation between the baseline simulated and the future climate projected at the nearest GCMs grid are adopted to modify the ratio of changes in monthly precipitation at local watersheds. The differences in monthly temperature between the baseline simulated and the future climate projected at the nearest GCMs grid are adopted to modify the changes in monthly temperature at local watersheds. For the 6 GCMs selected in this study the locations of the nearest grids to both watersheds are different due to different grid resolutions among these GCMs.

A stochastic weather generator was used as the temporal downscaling tool as applied in past studies (Li et al. 2009; Tung et al. 2014). Multimembers of daily temperature and precipitation were generated to reproduce the statistic of temperature and precipitation from observations for baseline and with projected changes by GCMs/scenarios outputs for future climate. The daily temperature is generated using the first-order Markov Chains by preserving the lag-1 correlation of observed daily temperature and standard deviation of the observed daily temperature in each month, while allowing the changes in monthly mean temperature adopted from GCMs projections. The daily rainfall is generated in two steps, generating the occurrence of precipitation and generating the amount of precipitation. In the generating occurrence of precipitation step, the conditional probability for a wet day following a wet day and the conditional probability for a wet day following a dry day are adopted from the observed data as references to generate the occurrence of precipitation with random numbers. If a wet day is generated, the distribution of precipitation is calculated with an exponential distribution with respect to the monthly precipitation, which allows the change in monthly mean precipitation adopted from GCMs projections. A total of 200 years of daily precipitation and temperature were generated for both the baseline period and future climate scenarios to be used as input for the GWLF model to simulate runoffs. Details of our stochastic weather generation approach can be found in Tung and Haith (1995).

2.2.4 Hydrological Model

The GWLF model is a lumped hydrological routing model. Major hydrological components, including evapotranspiration, surface runoff, infiltration, percolation, groundwater discharge, unsaturated zone, and shallow saturated zone, are considered through daily water balance routing as depicted in Fig. 3. Stream flow consists of runoff and groundwater discharges. Surface runoff in GWLF is computed using the Soil Conservation Service Curve Number method (SCS 1986). The evapotranspiration is estimated by a correction factor, accounting for different crop types and growing seasons, to the potential evapotranspiration estimated by the temperature-based Hamon equation (Hamon 1961). Infiltration to the unsaturated and shallow saturated zones equals the excess, if any, of rainfall less runoff and evapotranspiration. Percolation occurs when unsaturated zone water exceeds field capacity. Both daily precipitation and temperature are primary climatic forcing required to perform hydrological routing. The GWLF was selected to facilitate considering changes in precipitation and temperature, which are the most significant climatic variables that can be retrieved from GCM projections. In fact, other hydrological models might be used as long as the GCM projections can be implemented, such as HBV used in other studies. The water budget of each watershed is simulated independently. Five weather stations (marked with the diamond symbols in Fig. 1) were used for each watershed to estimate the average basin precipitation using the Thiessen polygon method. A detailed description of the GWLF hydrological model can be found in Haith et al. (1992).

3. RESULT AND DISCUSSION

3.1 Historical Trends of Temperature and Rainfall of the Study Area

Temperature trends of both Gilgel Abbay and Gumara watersheds are analyzed with the Bahir Dar and Debre Tabor weather stations, respectively. As depicted in Fig. 4, both stations recorded increasing temperatures over the 1983 - 2012 period. However, there was no clear trend in annual

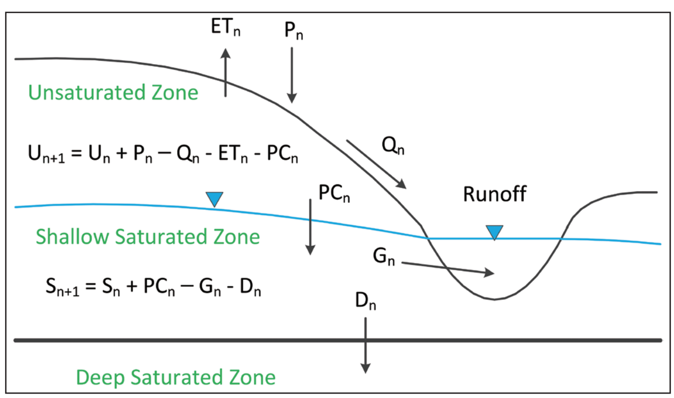

Fig. 3. Schematic diagram of GWLF hydrological routing model, where ET is evapotranspiration, P is precipitation, Q is surface runoff, and G is groundwater discharge, U is available moisture content of unsaturated zone, PC percolation from unsaturated zone into shallow saturated zone, D is deep seepage from shallow saturated zone into deep saturated zone, and the subscript "n" denotes the n-th day (modified after Haith et al. 1992). (Color online only)

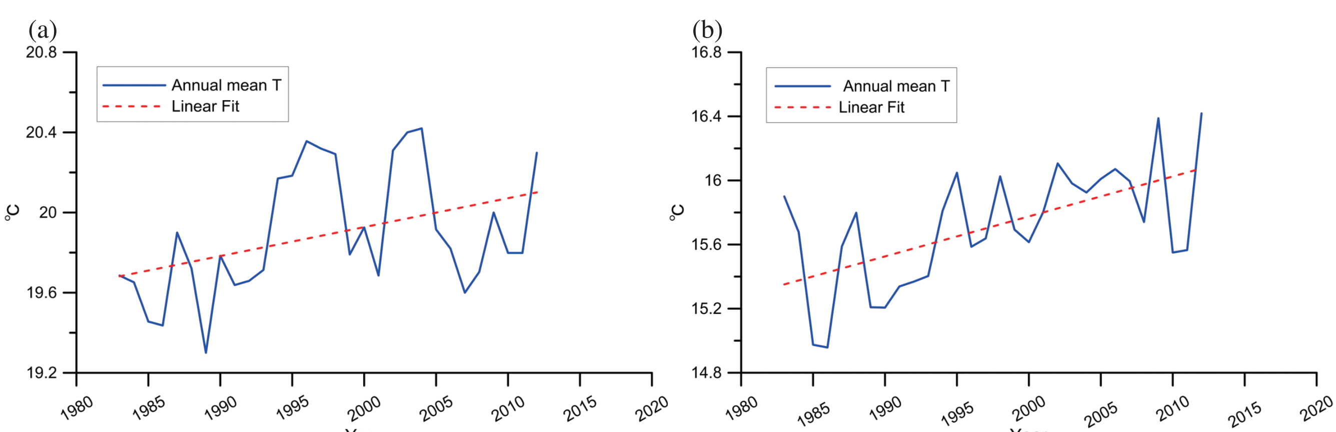

Fig. 4. Annual temperature trend at (a) Bahir Dar weather station at Gilgel Abbay and (b) Debre Tabore weather station at Gumara watershed. (Color online only)

precipitation (not shown here). The rainfall spatial distribution of Tana Basin estimated with weather stations marked with circle and diamond symbols, as depicted in Fig. 5a, shows an increasing trend from the eastern (Gumara) to the southern (Gilgel Abbay) catchments. This shows that wet season/monsoon precipitation is under the influence of ITCZ in which the eastern part gets less precipitation (Gumara) in comparison to the western part (Gilgel Abbay). This is in addition to the elevation effect over catchment area. Figure 5b represents data from four weather stations from both catchments. The peak rainfall at many of the weather stations was observed in July and August of the rainy season (June to September). Enyew et al. (2014) reported that precipitation in east Africa is dominated by the shift in the ITCZ. Taken together, the evidence from the meteorological stations shows that the temperature has been increasing while rainfall has been erratic over the catchment area.

3.2 Calibration of the GWLF Hydrological Model

The observed daily flow data from 1993 - 2012 at Gilgel Abbay and Gumara gauging stations (Fig. 1) collected by the MoWIE were used for the GWLF calibration. The GWLF calibration was done using trial and error experiments with coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), and root mean square error (RMSE) to evaluate the model skill. Figure 6 presents daily runoffs simulated by GWLF compared with the observed values. Values of R^2, NSE, and RMSE are given in Table 1. The results given in both Fig. 6 and Table 1 demonstrate that runoffs simulated by GWLF are acceptable. Among the parameters considered during GWLF model calibration, Soil Conservation Service curve number II (SCS 1986), rescission constant, initial unsaturated, and saturated soil moisture content, plant cover coefficient were found to be most sensitive.

3.3 Climate Change Impact Assessment

3.3.1 Projected Temperature

Similar to the historical climatology records, the projected temperature shows an increasing trend at both the Gilgel Abbay and Gumara watersheds. As can be seen in

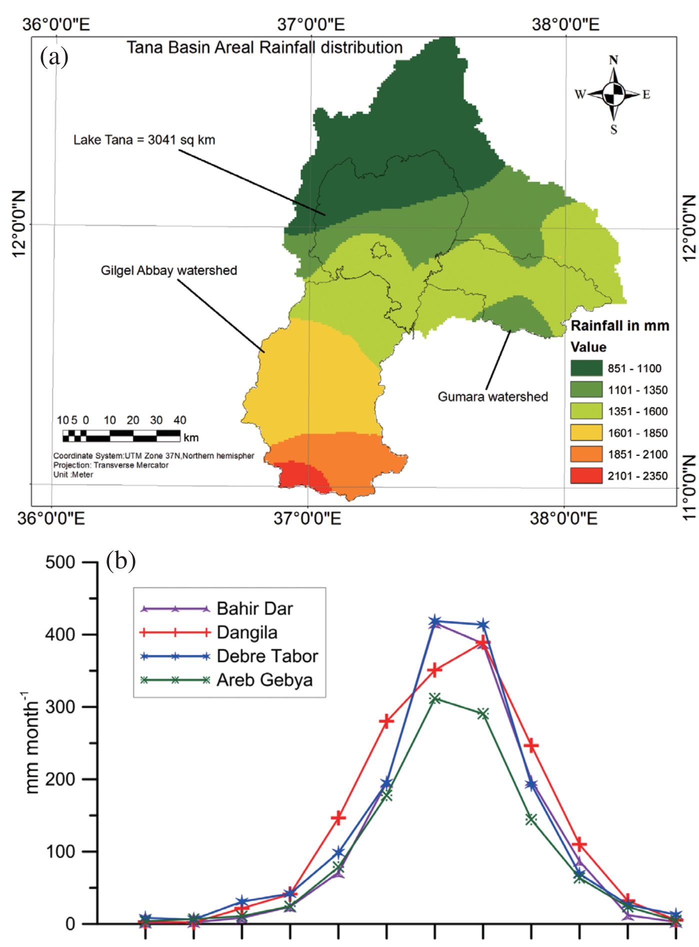

Fig. 5. (a) Spatial rainfall distribution depicted with 10 weather stations and (b) long-term average annual rainfall distributions at the four weather stations of Gilgel Abbay and Gumara watersheds. (Color online only)

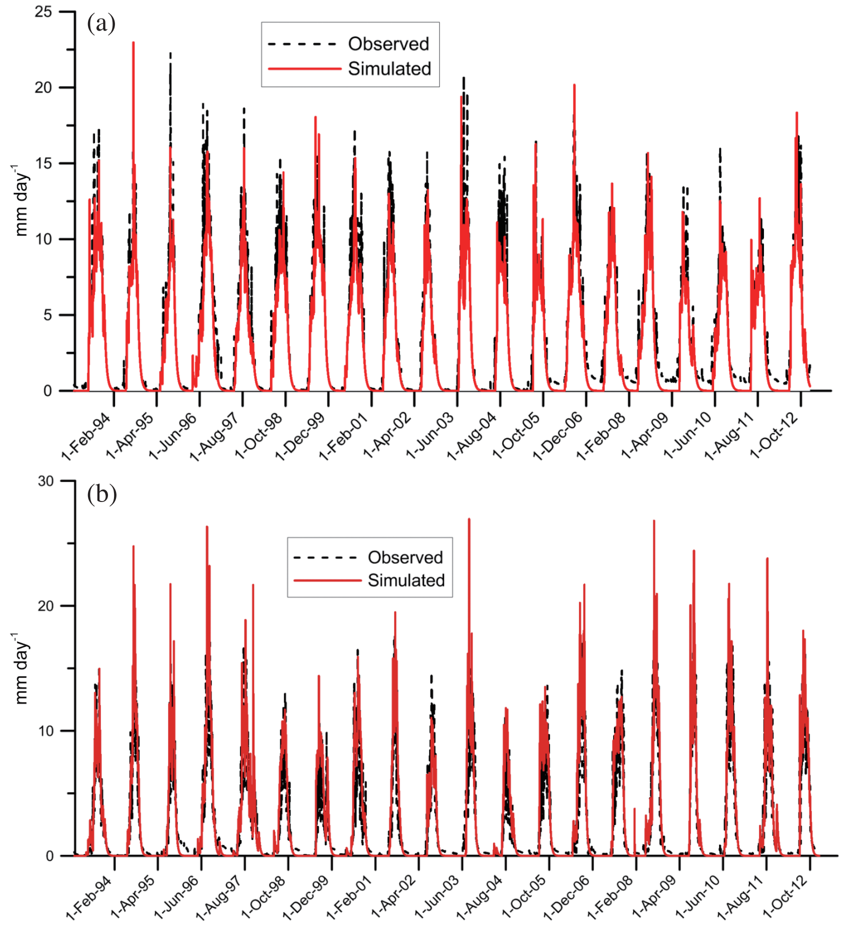

Fig. 6. Time series plot of observed and simulated daily runoff depth at (a) Gilgel Abbay and (b) Gumara gauge station for the period 1993 - 2012. (Color online only)

Table 1. Results of GWLF calibration from 1993 - 2012.

Objective function	Gilgel Abbay	Gumara
R^2 (coefficient of determination)	0.81	0.83
NSE (Nash-Sutcliffe efficiency)	0.80	0.78
RMSE (Relative mean square error) (mm day^{-1})	1.17	1.27

Fig. 7, among the 6 GCMs and two emission scenarios, eight cases from combinations of four GCMs and two emission scenarios show an increasing temperature trend at both watersheds. In both scenarios, the temperature is lower for the low emission scenarios (B1) relative to the high emission scenario (A2).

An important conclusion from the projected temperature is that, the projected temperature for 2020 - 2039 is increase as projected by INCM3, GFCM20, GFCM21, and IPCM4, while both CSMK3 and MPEH5 predict the reverse. More specifically, a maximum of 2.3, 2.2, 1.6, and 1.8°C increment is observed in INCM3, GFCM20, GFCM21, and IPM4 respectively at the Gilgel Abbay watershed and 2.2, 2.0, 1.3, and 1.0°C increments in IPCM4, INCM3, GFCM20, and GFCM21 respectively at the Gumara watershed. A maximum decrement of 2.5 and 2.2°C observed at the Gilgel Abbay watershed and 2.1 and 2.7°C observed at the Gumara watershed was projected by CSMK3 and MPEHS, respectively.

The ensemble average of the 6 GCMs results reveled that temperature tends to increase in the 2020 - 2039 period at both watersheds with 1.2 and 1.1°C at Gilgel Abbay and 0.8 and 0.7°C at Gumara with A2 and B1 emission scenarios, respectively. Likewise, Dile and Srinivasan (2014) reported that temperature at the Tana basin (Gilgel Abbay watershed) will increase by 0.5°C per decade from 2000 - 2100. It is worth noting that the projected temperature at Gilgel Abbay is slightly higher than that at Gumara. The difference stems from the difference in baseline temperature at the two watersheds, which in turn is explained by the elevation.

3.3.2 Precipitation

The projected precipitation, evapotranspiration and runoff are presented separately for the wet season (June to September) and dry season (October to May). The results are given as percentage change with respect to the baseline respective of each GCM (e.g., a change of 100% would imply a doubling of precipitation/runoff). Despite variations among GCMs projections, an increase in wet and dry season precipitation was found at both watersheds for all GCMs and in both scenarios, except for a slight decrease given by GFCM21 for the wet season at Gumara watershed, as shown in Fig. 8. The largest change relative to the baseline is observed in the CSMK3 GCM case with +45, +41, and +48% and 45% at both Gilgel Abbay and Gumara in A2 and B1 emission scenarios, respectively, in the dry season. The GFCM21 yields the smallest projected changes in dry season, respectively for A2 and B1 SRES, with +4, +2% at Gilgel Abbay and +8, +6% at Gumara. It even predicts a worst wet season with +2, +1% at Gilgel Abbay and -7, 3% at Gumara. These results are similar to those by Beyene et al. (2010) concluding a projected rainfall of -24 - 37% (2010 - 2039) based on 17 GCMs, on their study on the entire Nile Basin where Gilgel Abbay and Gumara watersheds are located. A recent study by Nigatu et al. (2016), also found similar conclusions that Lake Tana catchments show increasing rainfall with both A2 and B2 emission scenarios for the 21st century in comparison to the baseline.

In spite of these exceptions, however, there is general consensus on the direction that rainfall is likely to increase. The GFCM21 projections for the Gumara watershed wet season is an exception in this regard. Moreover, under both emission scenarios, the projected change in rainfall at the two watersheds for both seasons is more or less similar. This is also expected as the case of temperature, high rainfall is expected with A2 than B1 SRES. The projected rainfall change in the dry season is higher than that in the wet season due to low baseline rainfall in the dry season.

Among all GCMs and scenarios, there is a consistent finding of minor shift in seasonal rainfall pattern at both watersheds. Compared to the baseline, rainfall is projected to decrease at the beginning (June) but increase at the end (September). This trend is clearly observed by CSMK3 and GFCM20 for both watersheds, as presented in Fig. 9. This is also true for the other four GCMs, which are not shown here. Abdo et al. (2009) found similar rainfall shifts with A2 and B2 SRES for the Gilgel Abbay watershed. According to

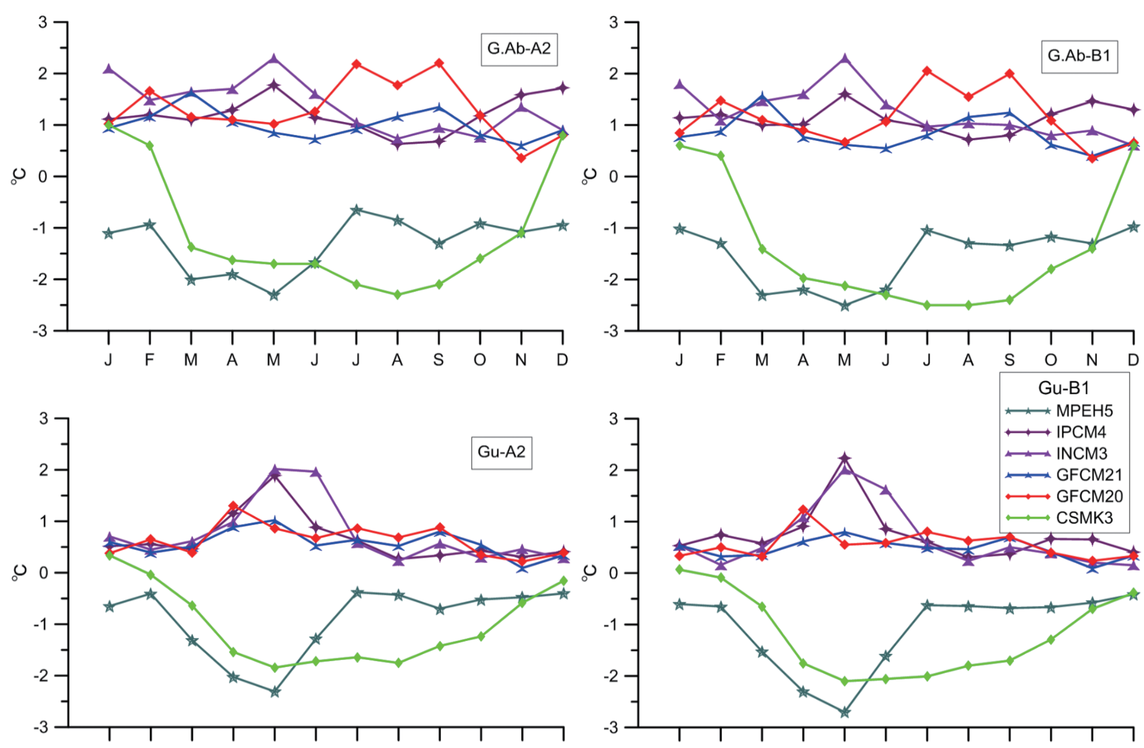

Fig. 7. Projected change in mean temperature at Gilgel Abbay and at Gumara watersheds in A2 and B1 emission scenario for the period of 2020 - 2039 where G.Ab-A2, G.Ab-B1 stands for Gilgel Abbay under emission scenario A2 and B1 whereas Gu-A2 and Gu-B1 stands for Gumara watersheds, under emission scenario A2 and B1, respectively. (Color online only)

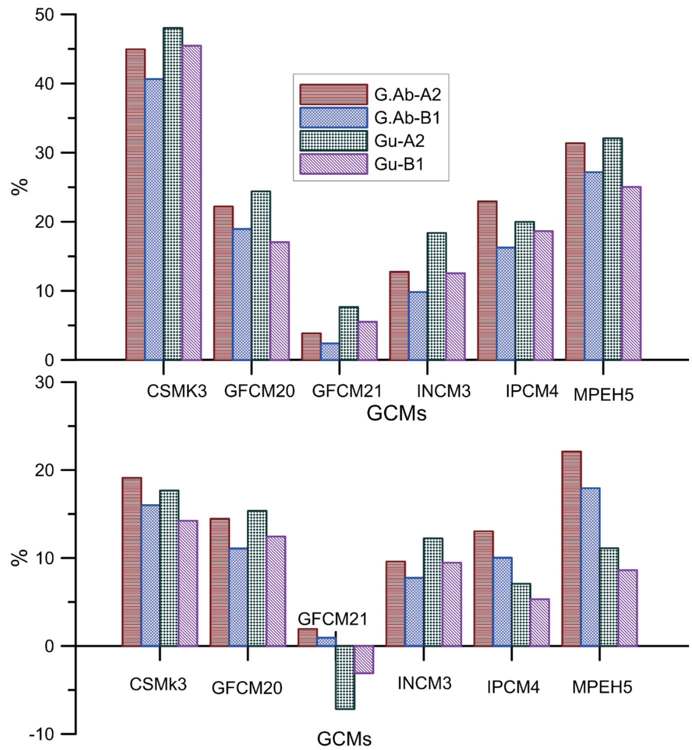

Fig. 8. Projected precipitation in dry season (top) and in wet season (bottom) in comparison to the baseline (1980 - 1999) in Gilgel Abbay and Gumara watersheds. (Color online only)

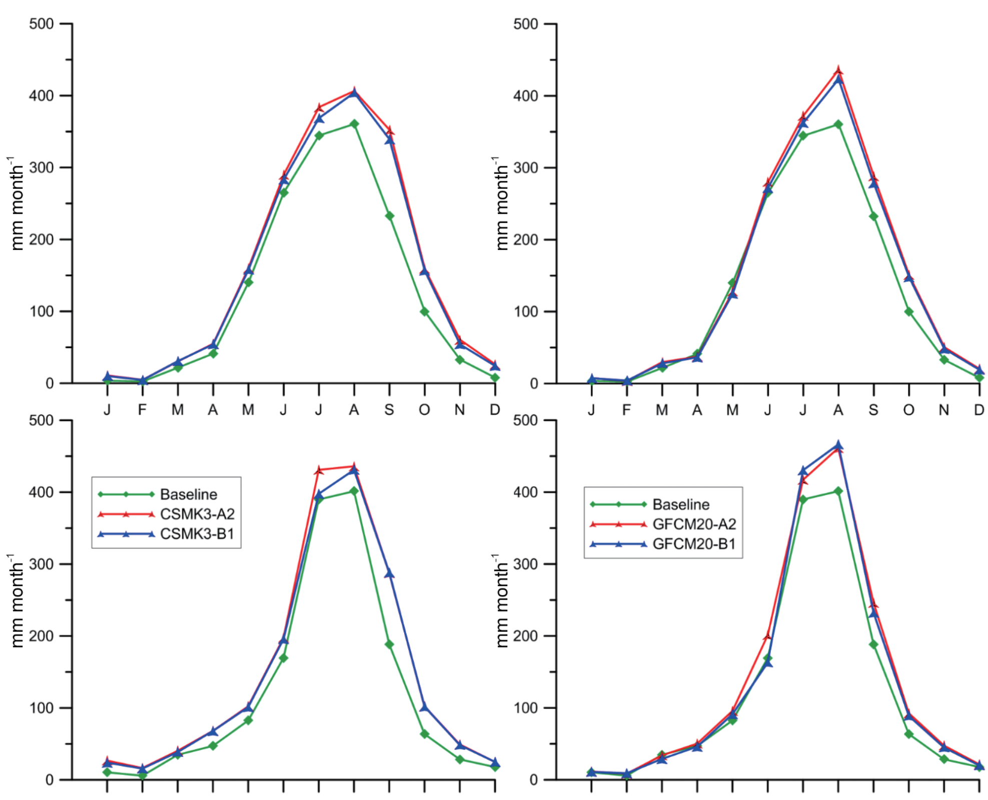

Fig. 9. Projected mean monthly precipitation in Gilgel Abbay (top) and in Gumara watershed (bottom) for 2020 - 2039. (Color online only)

their findings, the mean daily rainfall generally decreases at the beginning of the rainy season while it increases towards the end of the rainy season for both A2 and B2 scenarios in all future times. For a country in which the majority of the population's livelihood depends on rain-fed agriculture from wet-season precipitation, this result has paramount implication in informing the local farmers to prepare tillable lands for cultivation at the appropriate time.

In other words, an early warning system in the study area should improve the sowing and harvesting dates following the rainy season onset and offset. In general, projected future changes in mean seasonal precipitation for eastern Africa are not certain (IPCC 2001, 2007; UNECA 2011; Enyew et al. 2014). The high precipitation variability (around 40%) UNECA (2011) makes the prediction of future precipitation notably difficult at the sub regional and watershed level. With a high emission scenario, large areas of Africa would experience changes in December to February or June to August precipitation that exceed natural variability (IPCC 2001). Likewise, our studies found substantial variation among individual GCMs in dry season (October to May) and wet season (June to September) precipitation projections. This finding also agrees with Conway (2005) that significant inter-model differences in the projection and uncertainty about future precipitation changes and pattern over Ethiopia.

Different GCMs may give different projections in terms of magnitude and trend. Such inconsistencies in magnitude of projection may be attributed to the uncertainty associated with GCMs and scenarios (IPCC 2001, 2007; Li et al. 2009; Enyew et al. 2014). Intermodal inconsistencies in magnitude may be reduced using many GCMs to provide probabilistic estimates of climatic risk through ensemble model integrations (Hewitt 2004).

3.3.3 Evapotranspiration

The projected evapotranspiration by the 6 GCMs over the Gilgel Abbay and Gumara watersheds of the upper Blue Nile basin in the period 2020 - 2039 is given for the dry and wet seasons in Fig. 10. The projected change in evapotranspiration follows the projected change in temperature in both watersheds. In other words, GCMs which show temperature increase over the two watersheds compared to the baseline show an increase in evapotranspiration for 15 - 24.2% in the dry season and 5.5 - 21.4% in the wet season. Likewise, GCMs projections which show temperature decrease (CSMK3 and MPEH5); show a decrease of 2.9 - 10% and 6.8 - 24.5% with respect to the baseline. It is also important to note that trends are pronounced in the dry season (when it increases) and wet season (when it decreases). These results are in line with the historical weather pattern at the Tana basin where the average wet season temperature is nearly 2°C lower than that of the dry season.

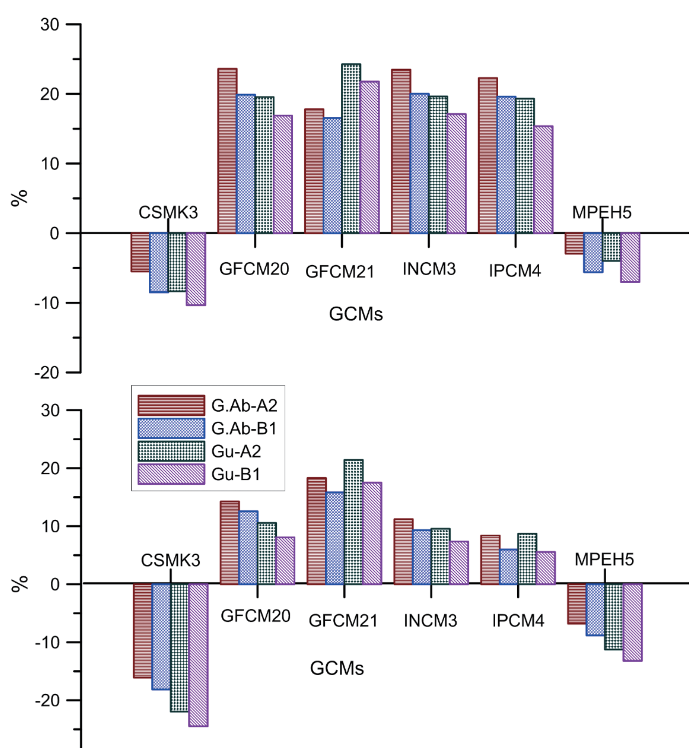

Fig. 10. Projected evapotranspiration changes in percentages for dry season (top) and wet season (bottom) of Gilgel Abbay and Gumara watersheds with reference to the baseline. (Color online only)

3.3.4 Runoff

Runoff is the main hydrological component highly influenced by climate change. Figure 11 presents the projected runoff changes in percentages for the Gilgel Abbay and Gumara watersheds under A2 and B1 emission scenarios for the dry season (top) and wet season (bottom). In Gilgel Abbay 6 - 58% and in Gumara 16 - 78 % increment of runoff is projected with respect to the baseline in the dry season. Whereas in the wet season, 4 - 38% increment of runoff at Gilgel Abbay and -10 - 17% variations of runoff are projected in Gumara with reference to the baseline.

Although there is substantial difference in the projection magnitude among the 6 GCMs, there is consistency in the projections for both watersheds in the dry and wet seasons. Both CSMK3 and MPEH5 projected higher increments of runoff in comparison with the other GCMs for both watersheds for both seasons, whereas GFCM21 projected relatively lower runoff in both emission scenarios. Generally, this result implies that there is an increase in runoff on average of 21 and 23% at Gilgel Abbay and 29.5 and 25% at Gumara watersheds with A2 and B2 emission scenarios, respectively. Our results are comparable with the findings of Dile et al. (2013).

Remarkable differences in projected runoffs are observed between the Gumara and Gilgel Abbay watersheds, which may lead to significant spatial differences between the two watersheds. For example, projected runoffs for the dry season at Gumara watershed are significantly higher than those for Gilgel Abbay by all GCMs with both emission scenarios, as shown in Fig. 11 (top). However, projected precipitation comparisons between the two watersheds are not that significant, as shown in Fig. 8 (top). The differences in projected changes in evapotranspiration can be used to explain such discrepancies between the two watersheds. The projected changes in evapotranspiration for Gumara watershed are generally lower than those for Gilgal Abbay watershed in the dry season, as shown in Fig. 10 (top). This also substantiates the findings of Setegn et al. (2011) that the stream flow changes are larger in magnitude than the precipitation changes. Similarly, Babatolu and Akinnubi (2014) also found 5.6% increase in annual precipitation resulting in 12.2% increase in annual runoff at the Niger River basin. We found that an increase of 23% (in ensemble average of 6 GCMs) precipitations change in dry season resulted in an increase of 46% runoff change relative to the baseline in this season at Gumara watershed.

Although there are differences among the projection magnitudes using different GCMs, the precipitation pattern generally dominates the change in runoffs in both seasons and at both watersheds for both A2 and B1 emission scenarios. This is verified by the projections shown by GFCM20,

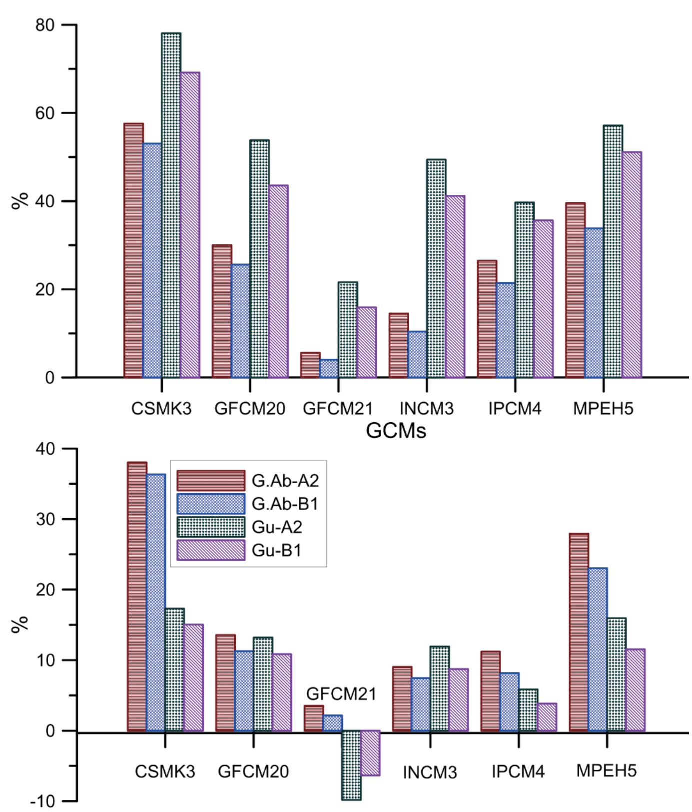

Fig. 11. Projected runoff change in percentage for dry season (top) and wet season (bottom) of Gilgel Abbay and Gumara watersheds with reference to the baseline. (Color online only)

GFCM21, INCM3, and IPCM4, which all show an increase in runoff with increased evapotranspiration as well. This trend is consistent with the finding of Setegn et al. (2011) that, in the Tana basin region the dominant factor controlling runoff depth is precipitation rather than evapotranspiration. Babatolu and Akinnubi (2014) in their study also reported that in the East Africa Region, there is high positive correlation between annual precipitations with annual runoffs.

Nevertheless, unlike Setegn et al. (2011) and Babatolu and Akinnubi (2014), we found that the role of evapotranspiration (in addition to the rainfall) in the wet season is important. Both CSMK3 and MPEH5 projected declined evapotranspiration in both watersheds [Fig. 10 (bottom)], while these two GCMs project higher runoff in wet season [Fig. 11 (bottom)] in comparison to other GCMs. GFCM21 projected lower runoff depth at both watersheds in the dry and wet seasons and projected relatively higher evapotranspiration in comparison to the other GCMs in both emission scenarios.

We took the ensemble average of runoffs projected by 6 GCMs with both high and low emission scenarios to calculate the runoff ratios presented in Table 2. The annual runoff will be increased by 18.0 and 20.3%, with respect to the baseline, at Gilgal Abbay and Gumara watersheds, respectively. Both watersheds show an increase in runoff ratio from 0.360 - 0.378 at Gilgel Abbay and from 0.268 - 0.289 at Gumara. This is attributed mainly to the increase in rainfall suppressing the increase in evapotranspiration. These factors enable additional inflow into Lake Tana in the 2020 - 2039 period from the two watersheds, similar to conclusions inferred by Beyene et al. (2010).

Another way of thinking is if more GCMs give an increased runoff projection, we may have more confidence that increased runoff might be likely in the future. In General, the runoff projection for these two largest (Gilgel Abbay and Gumara) inflow contributors of Lake Tana infer that there is a good future with respect to available water volume from the Lake for the 2020 - 2039 period. Since Lake Tana is the source of the Blue Nile River and the ongoing largest grand Renaissance Dam (which will be expected to produce bulk hydropower energy for east Africa) are fed by these Rivers, more climate impact assessment studies shall be done for this basin to have better prediction and minimize uncertainties. With regard to this, Li et al. (2009) indicated projected hydrological impacts in change of percentage are subject to discrepancies among different scenarios. Thus, as many GCMs as possible and scenarios shall be employed for impact assessment. Because of the uncertainty, we did not intend to conclude which GCM projection is the best. Therefore, the numbers presented in this study should not be directly used for engineering design.

4. CONCLUSIONS

The hydrological cycle, notably fresh water resources, is prone to the direct influences of climate change. The effects are more pronounced in regions like the Horn of Africa. This paper assessed the impact of climate change on both the Gilgel Abbay and Gumara watersheds that drain into Lake Tana, the upper Blue Nile basin, using a physical based GWLF hydrological model. For the future impact assessment 6 GCMs with both A2 and B1 scenarios of the SRES were adopted for the period 2020 - 2039. A weather generator model was employed to generate daily air temperature and precipitation based on different climate scenarios by modifying the observed temperature and precipitation data. These modified data of daily temperature and precipitations were applied to drive the GWLF hydrological model to simulate future runoffs.

Despite projected percentage results with respect to the baseline showing substantial differences among the different GCMs, increasing temperature in four GCMs, increasing precipitation in five GCMs, increasing evapotranspiration in four GCMs, and increasing of runoff in all GCMs, except for GFCM21 for the wet season runoff, were observed for the Gumara watershed with both high and low emission scenarios for both dry and wet seasons. All projected changes with the A2 scenario were higher than those with the B1 scenario.

For both watersheds, changes in precipitation dominate the runoff variations. Increased precipitation in the wet season in Gumara watershed makes the wet season wetter and induces high runoff. This will have deleterious consequences in the near future in the local community as the watershed is naturally vulnerable to frequent flood risks. The increased runoff for Gilgel Abbay and Gumara rivers may be a good opportunity for the sustainability of Lake Tana and for the ongoing grand Renaissance Dam, which will be expected to

Table 2. Summary of projected (2020 - 2039) annual runoff in comparison to the baseline 1980 - 1999.

Watershed	Runoff (mm year^{-1})			Runoff Ratio (Q/P)	
	1980 - 1999	2020 - 2039	$(Q_P - Q_b)/Q_b$	1980 - 1999	2020 - 2039
Gilgel Abbay	559.2	660.3	18.0	0.360	0.373
Gumara	386.1	464.5	20.3	0.268	0.289

Note: Q_b and Q_P are baseline and projected runoffs, respectively.

produce bulk hydropower energy for East Africa. However, the magnitude of projected changes varies across models and scenarios. This is common in climate related impact assessment studies. Future studies aimed at assessing the impact of climate change on the upper Blue Nile basin shall be aware of uncertainties in climate projections. The applicability of adaption measures should be evaluated periodically for having the flexibility to amend correspondent actions as the proposed concept of adaption pathway.

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