Article

Impact of climate change on streamflow hydrology in headwater catchments of the Blue Nile basin, Ethiopia

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Abstract: This study assessed the impact of climate change on water availability and variability in two subbasins in the Upper Blue Nile Basin of Ethiopia. Downscaled future climate data from HadCM3 of A2 (medium-high) and B2 (medium-low) emission scenarios were compared to the observed climate data for a baseline period (1961 to 1990). The emission scenario representing the baseline period was used to predict future climate and as input to a hydrologic model to estimate the impact of future climate on the streamflow at three future time horizons 2020 - 2045, 2045 - 2070 and 2070 - 2100. Results suggest that medium-high emission scenario best represents the local rainfall and temperature pattern. With A2 scenario, daily maximum/minimum temperature will increase throughout the future time horizons. The minimum and maximum temperature will increase by 3.6°C and 2.4°C, respectively, towards the end of the 21st century. Consequently, potential evapotranspiration is expected to increase by 7.8%, though trends in annual rainfall do not show statistically meaningful trends between years. A notable seasonality was found in the rainfall pattern such that dry season rainfall amounts are likely to increase and wet season rainfall to decrease. The hydrological model indicated that the local hydrology of the study watersheds will be significantly influenced by climate change. Overall, at the end of the century, streamflow will increase in both rivers by up to 64% in dry seasons and decrease by 19% in wet seasons.

Keywords: Climate change; HBV; climate projection; Ethiopian highland

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1. Introduction

Greenhouse gases emissions have significantly increased since the industrial revolution and led to global warming [1]. According to the Intergovernmental Panel on Climate Change [IPCC, 2], the atmospheric concentration of CO_2 has increased from 280 ppm in 1750 to 367 ppm in 1999. The concentration increased to over 400 ppm in 2015 and it is expected to reach 463-623 ppm by 2060 and 470-1099 ppm by 2100 [3]. Scientific evidence indicates that increased greenhouse gas emissions will cause an increase in average temperature of the earth by up to 1.4-5.8°C by the end of the century [4-6]. Recently, several places across the world have experienced record-breaking meteorological extremes since measurements began [7,8].

Climate change will have a profound impact on the availability and variability of fresh water as the frequency of climatic extremes increases in response to global warming [9]. The uncertainty of the availability of water resources will affect agricultural production, challenge socio-economic systems, and threaten environmental sustainability. The effect of climate change will be significant particularly in developing countries where their economy is heavily dependent on agricultural production [10,11]. The IPCC suggested that Africa as one of the most vulnerable continents to climate change [10]. Ethiopia is one of the African countries whose economy is largely dependent on agriculture [11-13]. Therefore, the country's economy is subjected to a direct impact of climate change.

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A large portion of lands in Ethiopia is arid or semi-arid and these poorly managed lands can easily degrade with increasing climatic extremes and desertification. It is therefore important to understand the impact of climate change on water resources to implement appropriate climate change adaptation and mitigation strategies. Expansion of small scale irrigation is one of the mitigation strategies under consideration where dry season streamflow is reliable [14-16]. However, implementation of such strategies requires a thorough assessment of the impact of climate change on streamflow that is highly sensitive to climate, especially to changes in precipitation, snow regime and evapotranspiration [17,18]. Climate change scenarios from either General Circulation Models (GCMs) or simple analog models are frequently used to assess the hydrological impacts of climate change [19-22]. Since the impact of climate change can be significantly variable in different regions, it is important to conduct such study at critical agro-ecological regions to develop and implement adaptation and mitigation strategies.

The objective of this study is to evaluate the impact of climate change on the water resources availability of Beles subbasin in the upper Blue Nile basin using projected climate data and hydrological modeling. The basin is considered as one of the growth corridors in Ethiopia where large-scale development projects such as the Grand Ethiopian Renaissance Dam (GERD) and the Tana-Beles sugar factory are underway.

2. Materials and Methods

2.1. Study area

The study area is located in the Beles basin in the western part of the Upper Blue Nile Basin, Ethiopia. The Beles basin (10°20′-12°00′N and 35°00′-37°00′E) represents 8.0% (176,000 km²) of the Blue Nile basin (Figure 1). The basin is gauged at two locations: one at the outlet of Main Beles and another at the outlet of Gilgel Beles, with a catchment area of 3,485 km², and 742 km², respectively (Figure 1). The Gilgel Beles watershed (average altitude of 1,735 m) is situated at a higher altitude than the Main Beles (average altitude of 1,460 m). Rainfall in the area is unimodal with a prolonged dry spell from November to May followed by a wet season from June to October. The study area receives ~70% - 80 % of the total rainfall between June and September.

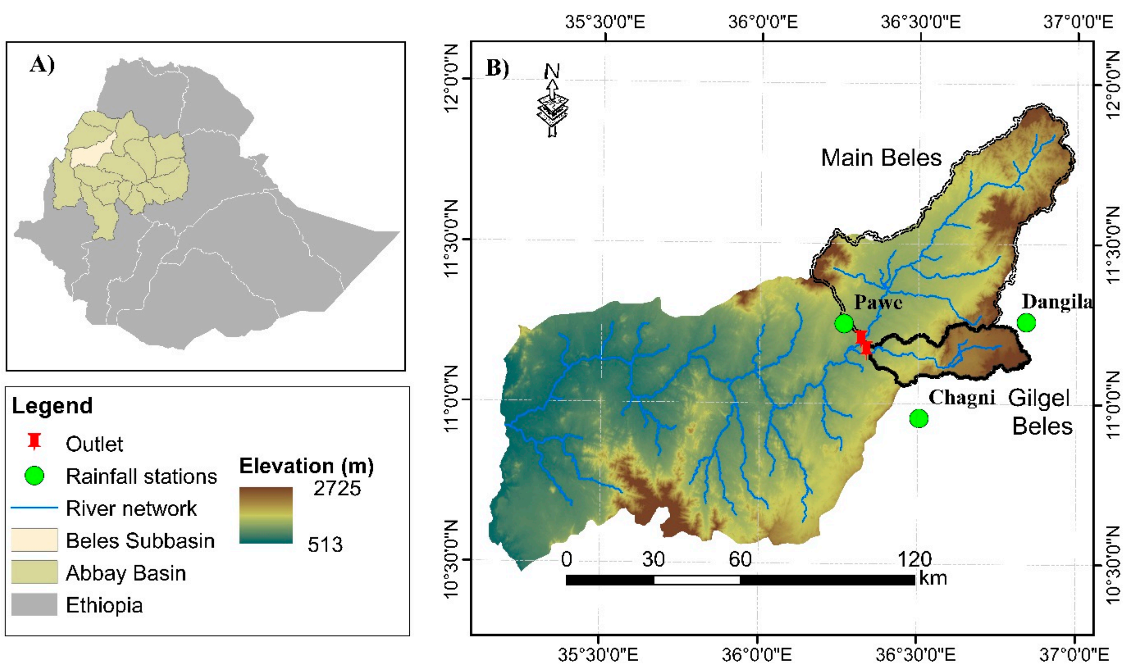

Figure 1: Location of the Main Beles and Gilgel Beles Subbasins in the Upper Blue Nile basin, Ethiopia. A) Ethiopia major river basins, Blue Nile Basin and Beles Subbasin. B) River network of Main and

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Gilgel Beles and rainfall gauging stations with 30 m resolution Digital Elevation Model (DEM) as a background.

2.2. Temporal and spatial data

Temporal data such as climatic and hydrological are required to simulate and calibrate a hydrological model. Meteorological stations located inside the study subbasins do not have continuously recorded daily climatic data for a longer period. However, the nearby stations Dangila, Chagni, and Pawe have a longer period daily rainfall and temperature data. Climatic variables (rainfall, maximum/minimum temperature, relative humidity, wind speed and sunshine hours) are only available at Dangila station. Streamflow is observed twice a day at twelve-hour interval at the outlets of Main Beles and Gilgel Beles river gauging stations. Figure 2 presents the average monthly flow of Main Beles and Gilgel Beles for the period 1998–2005.

The 30 m resolution Digital Elevation Model (DEM) was used to delineate the watershed, generate the drainage pattern and associated physiographic attributes. The land use and soil data were obtained from the Ethiopian Ministry of Water and Energy. The land use data indicated that agricultural land accounts for 73% and 49% of the Gigle Beles and Main Beles subbasins, respectively. Grassland is the second major land use type in Gilgel Beles subbasin (26.7%) while bushland (37%) is for Main Beles subbasin. The soil for the Gilgel Beles subbasin is dominated by Alisols which contains higher clay content with a low base saturation and susceptible to erosion [23]. The major soil for the Main Beles is Fluvisols (32% silt and 61% clay) which is categoriezed as young soils with a good natural fertility [23].

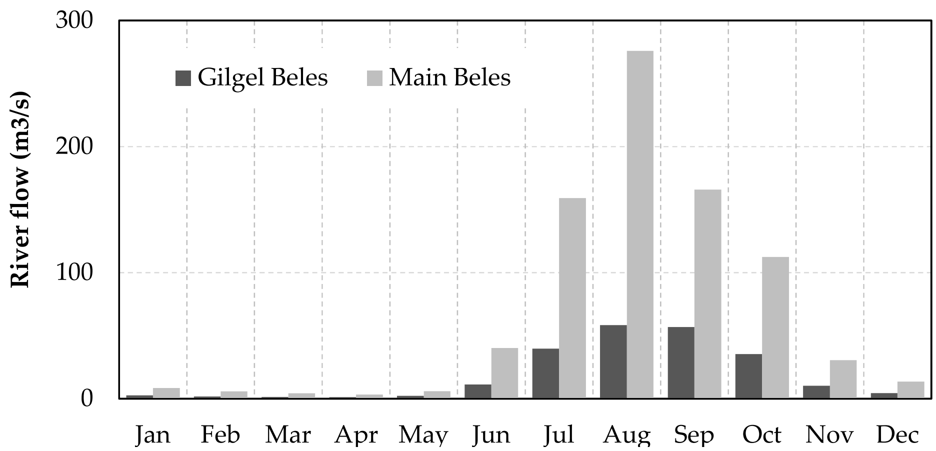

Figure 2: Average monthly streamflow of Main Beles and Gilgel Beles for the period 1998 to 2005.

2.3. Methods

The impact of climate change on streamflow was studied in three steps. Initially, a semi-distributed hydrological model called Hydrologiska Byråns Vattenbalansavdelning [HBV, 24] was calibrated to simulate the observed flow. The calibrated model was validated with an independent dataset. Thereafter, the General Circulation Model (GCM) data was downscaled using statistical downscaling model [SDSM, 25]. The A2 (medium-high) and B2 (medium-low) emission scenarios were downscaled to represent the future climate at subbasins level. The SDSM downscaled future climate was compared with the observed data for the baseline period. Finally, the downscaled future climate data, which captured the gauged climate data in the baseline period, was used as input to the calibrated and validated HVB model to evaluate the effect of future climate data on the streamflow of Main Beles and Gilgel Beles subbasins.

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2.3.1. Hydrological model description

The HBV model is a semi-distributed conceptual hydrological model [24,26]. In HBV, a watershed is divided into sub-watersheds and further into elevation and land use zones. The model simulates daily runoff from daily rainfall, temperature, long-term average monthly potential evapotranspiration, landscape characteristics and observed runoff data for calibration. The general water balance is described as:

$$P - E - Q = \frac{d}{dt}[SP + SM + UZ + LZ + lakes] \quad (1)$$

where: P: precipitation, E: evapotranspiration, Q: runoff, SP: snowpack, SM: soil moisture, UZ: runoff from the upper ground zone, LZ: runoff from the lower ground zone, lakes: Lake volume.

The model consists of subroutines for precipitation and snow accumulation, soil moisture accounting, response routine, transformation function and simple routing procedure. Precipitation and snow accumulation routine are computed separately for each elevation/vegetation zone within the sub-basin [24]. A threshold temperature separates snow and rainfall. Soil moisture accounting controls the runoff formation. Soil moisture accounting routine is based on three parameters Beta, LP, and FC. Beta controls the contributions to the response function ($\Delta Q/\Delta P$) or the increase in soil moisture storage (1- $\Delta Q/\Delta P$) from each millimeter of rainfall or snowmelt. LP is a soil moisture value above which evapotranspiration reaches its potential and FC is the maximum soil moisture storage (in mm). Response routine transforms the excess water from the soil moisture zone. The response routine consists of upper and the lower linear reservoirs. The upper reservoir is coupled to the soil moisture zone by seepage. When the seepage from the soil moisture routine exceeds the percolation capacity, the upper reservoir starts to fill and at the same time, the water will percolate to the lower reservoir [27,28]. The lower reservoir represents the groundwater that contributes to the baseflow.

2.3.2. Model calibration, validation, and performance evaluation

A semi-automated approach was applied to calibrate the HBV model calibration process. Initially, minimum and maximum limits of the parameters were set and automatic calibration was performed. Thereafter, manual calibration was used to refine the parameters. The model was calibrated for the period 1999 to 2003 and validated for the period 2004 and 2005. Percent Bias (PBIAS), Nash-Sutcliffe Efficiency (NSE) and Coefficient of Determination (R-square) were used to evaluate the model performance.

2.3.3. Future climate data

Climate scenarios are used to understand the plausible future climate. They are also used to quantify the relative change in the current and future climate, which is often used as an input to the hydrological models to assess the impact of climate change on hydrological systems, for example as in this study. There are different climate scenarios for climate change studies [29-33]. GCM based scenario (Dibike and Coulibaly, 2005; Roudier et al., 2011) and Synthetic scenario [2] are often used to project future climate [30,33,34]. This study used a general circulation model (GCM) based scenario to predicted the effect of future climate on the river flow. A scenario-based GCMs are the most common method of developing climate scenarios to quantify and assess the plausible impact of climate change. GCMs are required to project and quantify the relative change of climate variables between the current and future time horizon [35,36]. In turn, future climate data can be used as input to the hydrological model to access the effect of climate change on the river flow.

There are several GCM models that include atmosphere, ocean, land surface and sea ice components [37]. This study used the Hadley Center Coupled Model version 3 (HadCM3), which is a coupled atmospheric-ocean. HadCM3 is developed at the Hadley Center of the United Kingdom National Meteorological Service. HadCM3 was selected because of its wide applications [19,38,39]. In 1996, the IPCC has developed four different storylines emission scenarios described under Appendix A. In this study, scenario A2 and B2 were used. A2 scenario is based on high population

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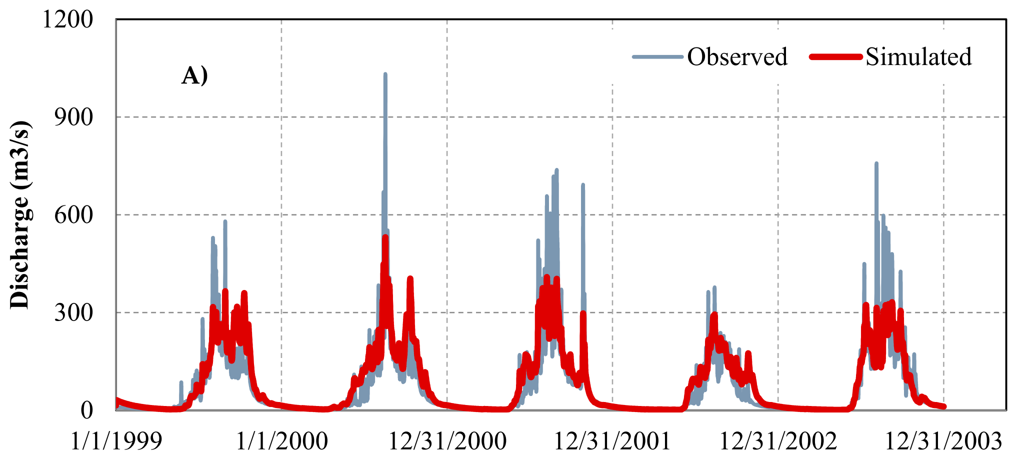
growth it describes very heterogeneous world with a high population growth while B2 represents a world with an emphasis on a local solution to a continuous global population increase at a rate lower than A2 [40].

The SDSM was used to downscale coarse resolution GCM climate data to local or watershed level. The downscaled data includes rainfall, maximum and minimum temperatures for the study site. SDSM requires a long-term meteorological data to develop multiple linear regression equations between the predictor and predictand [25,41]. The predictor variables provide daily information about large-scale atmosphere condition, while the predictand describes the condition at the local level (Ghosh and Mujumdar, 2008; Wilby et al., 2004). In this study, the Dangila climatic station, which has a longer time recorded data of rainfall and the maximum/minimum temperature was used to downscale HadCM3 future climate data of A2 and B2 emission scenarios. The performance of the downscaling was evaluated using the observed historical data for the baseline period (1961 to 1990). The calibrated and validated SDSM model was used to predict the future climate for three-time horizons representing 2020-2045 (2030s), 2045-2070 (2060s), and 2070-2100 (2080s). The potential evapotranspiration for the baseline and for the future time horizons was estimated using the FAO modified Penman-Monteith approach [42].

3. Results and Discussion

3.1. Model calibration and validation

The HBV model calibration showed a reasonable agreement with an NSE of 0.66 and 0.64 for Main Beles and Gilgel Beles, respectively. Figure 3A and 3B shows a comparison of simulated and observed daily streamflow of Main Beles and Gilgel Beles, respectively. Table 1 presents the calibrated model parameters and the corresponding statistical goodness-of-fit of Main and Gilgel Beles subbasins.



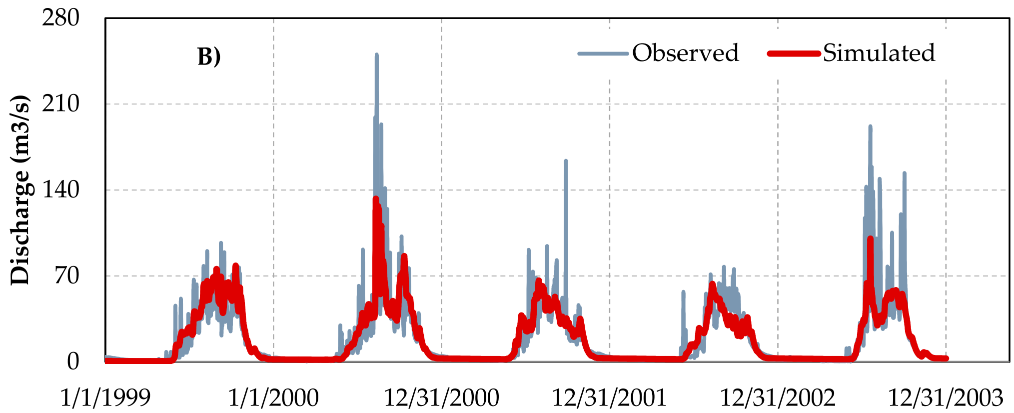


Figure 3: Comparison of simulated and observed flow for the calibration period (1999 to 2003). A) Simulated and observed flow of Main Beles; B) Simulated and observed flow of Gilgel Beles.

The simulation for the calibration period did not capture peak flows very well. The single peaked high streamflows are often associated with extremely high rainfall events and perhaps occur at a time scale smaller than the daily time step of the simulation period. Peak flows often occur after the catchment's time of concentration is reached, which occurs after the entire or a large portion of the catchment contributed streamflow to the subbasin outlet. However, for this study, only three rainfall gauging stations located outside of the subbasins are used to represent the subbasins areal rainfall. This may increase the uncertainty in the spatial distribution of and lead to underestimation of the peaks.

Table 1: HBV model calibrated parameters and model performance for the Main and Gilgel Beles subbasins.

Parameter	Alfa	Beta	FC	K4	KHQ	LP	PERC	NSE [-]	PBIAS [%]	R-square
Main Beles	**1.1**	**1**	**1200**	**0.002**	**0.082**	**0.82**	**0.4**	**0.64**	**-10**	**0.66**
Gilgel Beles	**0.75**	**1**	**450**	**0.002**	**0.08**	**0.76**	**0.55**	**0.66**	**-5**	**0.67**

The calibrated model parameters of Main Beles and Gilgel Beles were similar except for the maximum soil moisture holding capacity of the soil (FC) (Table 1). FC value of Main Beles was more than double to that of Gilgel Beles. This was exhibited in the observed streamflow where the runoff yield of Gilgel Beles (800 mm) was close to two folds of Main Beles. The high FC value in the Main Beles suggests that a significant amount of water can be retained in the soil, which will be lost later via evapotranspiration and/or as baseflow compared to Gilgel Beles.

The calibrated models were evaluated with an independent input data for the period from 2004 to 2005, and the result showed that the calibrated model performed reasonably well with an NSE value of 0.75 and 0.61 for Main Beles and Gilgel Beles, respectively. Therefore, the calibrated models together with downscaled future climate data were used to study the impact of future climate data on streamflow.

3.2. Future climate data

3.2.1. Downscaled precipitation, maximum and minimum temperature for the baseline period

The downscaled maximum and minimum temperature for the baseline period using HadCM3A2a and HadCM3B2a model outputs captured the observed monthly temperature

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distribution reasonably well. The maximum temperature was overpredicted by both models in February and March while underpredicted in April to August, November, and December. The maximum difference between predicted and observed maximum temperature for both model outputs were 0.5°C, which occurred in February. In both models, the monthly minimum temperature was overpredicted except in June, July, and October. The maximum model output difference between predicted and observed minimum temperature in both model outputs was ~0.5 °C in September and October. The difference between predicted and observed long-term monthly maximum/minimum temperatures between the two models were not significantly different. Therefore the downscaled temperature from both model outputs could be used to predict the future temperature in both subbasins.

The observed rainfall amounts were not reasonably captured by either of the downscaled climate scenarios because of the complex rainfall formation process [20]. Moreover, the coarse spatial resolution of the GCM models makes it difficult to adequately capture the observed rainfall pattern [19,43]. The difference between average monthly observed and predicted rainfall was ~9.9 mm/month and 13.5 mm/month for HadCM3A2a and HadCM3B2a model outputs, respectively. Eventhough there was some difference between the observed and predicted rainfall for the baseline period, the HadCM3A2a model output was better in capturing the temporal variation of the observed rainfall than the HadCM3B2a model output. Therefore, the HadCM3A2a model output (medium-high emission) was chosen to study the impact of future climate on the streamflow.

3.2.2. Downscaled precipitation, maximum and minimum temperature for future time horizon

The projected maximum and minimum temperature from A2 scenario showed an increasing trend for all future time horizons (Figure 4 and 5). In the A2 scenario, the projected temperature in the 2030s indicated that maximum and minimum temperature may increase by 0.6 and 1.0°C from the baseline period. In the 2060s, the maximum and minimum temperature will increase by 2.2°C and 1.4°C from the baseline period, respectively. In the 2080s, the maximum and minimum temperature will increase by 2.4 and 3.6°C from the baseline period. For the future time horizons, the rate of change of maximum temperature will be greater than the minimum monthly temperature.

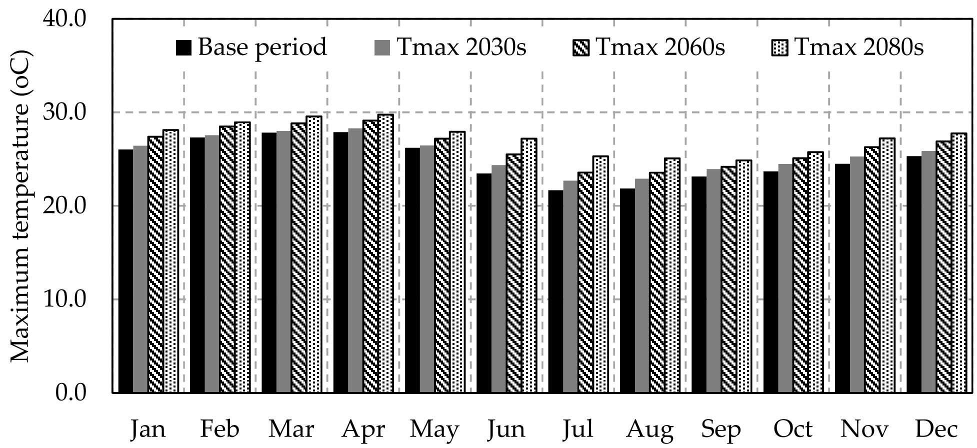

Figure 4: Long-term average monthly maximum temperature for baseline period and future time horizons (2030s, 2060s and 2080s) in the Main Beles and Gilgel Beles subbasins.

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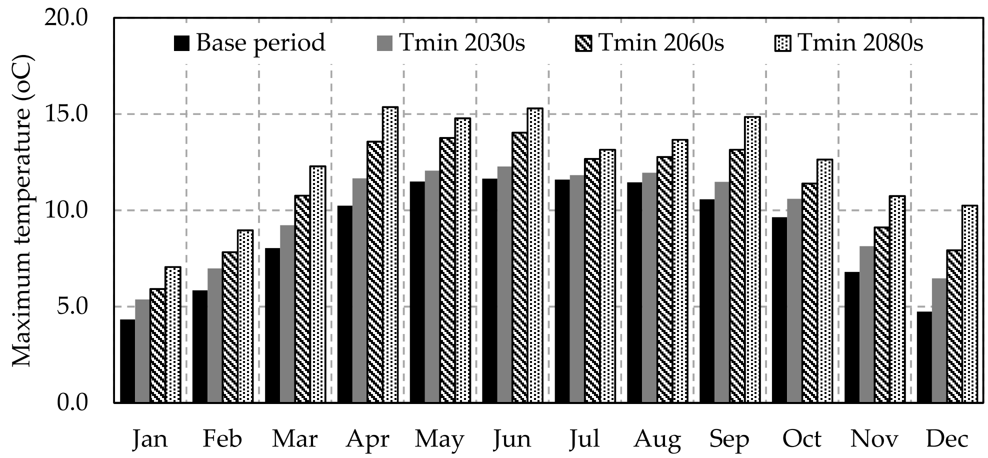

Figure 5: Long-term average monthly minimum temperature for baseline period and future time horizons (2030s, 2060s and 2080s) in the Main Beles and Gilgel Beles subbasins.

The long-term average monthly potential evapotranspiration was estimated for the baseline period and for the projected time horizons using the maximum and minimum temperature (Figure 6). The result indicated that the potential evapotranspiration may increase throughout the coming century. The average monthly potential evapotranspiration may increase by 2%, 4.7%, and 7.8%, in the 2030s, 2060s, and 2080s, respectively. The increasing temperature due to climate change may affect soil water balance by increasing soil evaporation and plant transpiration; thereby affecting crop growth and agricultural productivity [44].

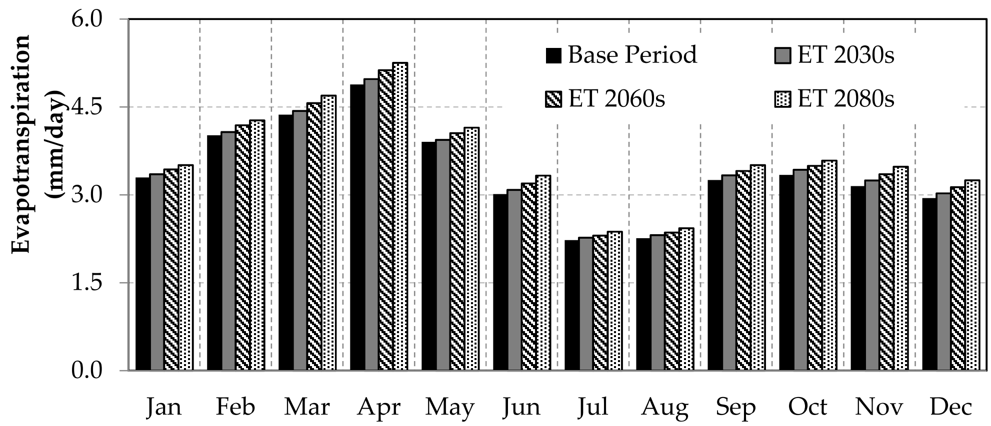

Figure 6: Long-term mean monthly potential evapotranspiration for baseline period and future time horizons (2030s, 2060s and 2080s) in the Main Beles and Gilgel Beles subbasins.

The average annual projected rainfall was estimated to increase by 2.3% in the 2030s and expected to increase by 2.6% and 3.1% in the 2060s and 2080s, respectively. However, the monthly rainfall projection for the coming century did not show a consistent trend, unlike the temperature, which has indicated a consistent increasing trend throughout all time horizons (Figure 7). The projected rainfall showed a decreasing trend in May and June (months before the beginning of the major rainfall season) and an increasing trend was observed in September, October and November (these are months after the major rainfall season) in the three-time horizons. The major rainfall months (June and July) did not show a consistent trend. Therefore, this suggests that climate change may shift the rainfall pattern in the Main Beles and Gilgel Beles subbasins.

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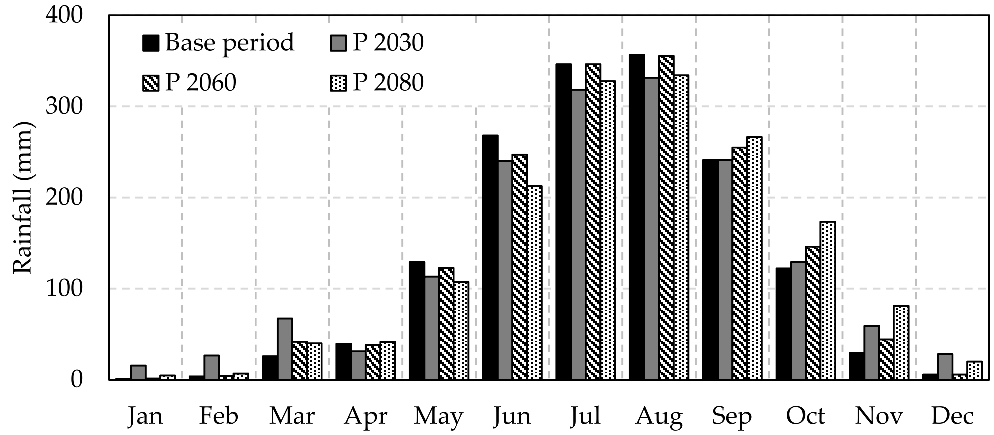


Figure 7: Average monthly rainfall during the baseline period and future time horizons (2030s, 2060s and 2080s) in the Main Beles and Gilgel Beles subbasins.

The projected rainfall showed an increasing rainfall trend in the dry season including October to March and a decreasing trend in April through June, which is not the major rainfall season. The increasing rainfall in the dry season may be used to supplement dry season irrigation.

3.3. Impact of climate change on the hydrology

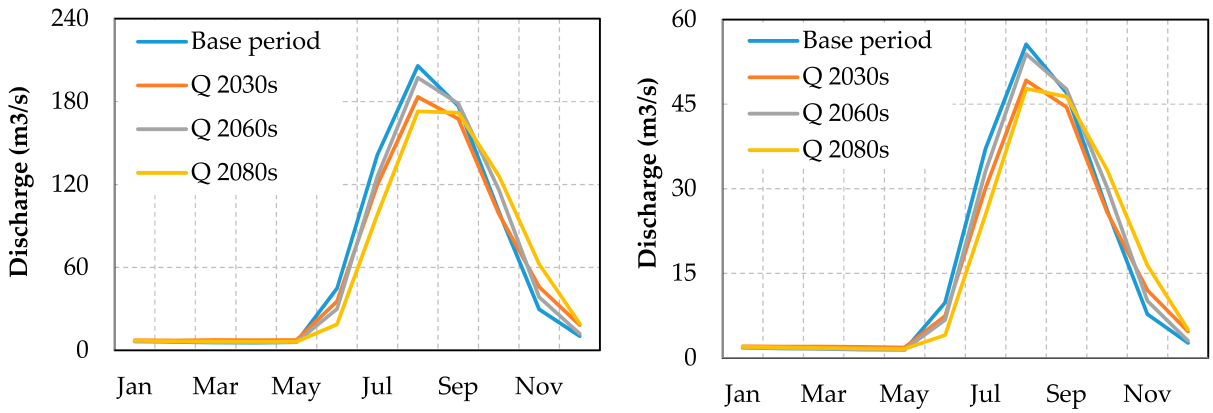
The projected rainfall, temperature and potential evapotranspiration values were used as input to the calibrated and validated HBV model for each future time horizons. The HBV model was used to evaluate the impact of projected climate data on the hydrology of Main Beles and Gilgel Beles subbasins for the three-time horizons: 2030s, 2060s and 2080s.

Hydrological impact of climate change in the Main and Gilgel Beles estimated by the HBV is summarized in Table 2 and Figure 8A and 8B. Average annual streamflow may decrease from baseline period, during all time horizons 2030s, 2060s, and 2080s. The average annual streamflow may decrease by up to 4.9% in Main Beles subbasin in the 2080s. While for the Gigel Beles, streamflow will reduce by up to 5.4% during the 2030s.

The seasonal variation of runoff of the projected climate from the baseline period was computed for wet and dry season (Table 3). The wet season includes June to September and the dry season includes the other eight months. The dry season average streamflow of Main Beles may increase by 45%, 16% and 64% from the baseline period in the 2030s, 2060s, and 2080s, respectively. While for the Gilgel Beles flow may increase by 44%, 16%, and 65% in 2030s, 2060s, and 2080s, respectively (Table 3). The average wet season streamflow may decrease for the coming century in both subbasins. For example, the average wet season streamflow for Main Beles will decrease by 11%, 7% and 19% in the 2030s, 2060s, and 2080s, respectively and for Gilgel Beles the average wet season flow will decrease by 12%, 6%, and 17% in the 2030s, 2060s, and 2080s, respectively (Table 2).

Table 2: Average annual streamflow and change in average seasonal stream flow between the three-time horizons from the baseline period.

Subbasins	Annual average streamflow change (%)			Change in average dry season streamflow (%)			Change in average wet season streamflow (%)		
	2030s	2060s	2080s	2030s	2060s	2080s	2030s	2060s	2080s
Main Beles	-4.48	-1.36	-4.96	45	17	64	-11	-7	-19
Gilgel Beles	-5.40	-0.59	-3.52	44	16	65	-12	-6	-17



(A) **(B)**

Figure 3: Average monthly streamflow for the baseline period and for the projected time horizon for (a) Main Beles and (b) Gilgel Beles.

The hydrograph for the monthly streamflow indicated that there may be an increase in both subbasins in the dry season. For example, in the 2030s, an increase in streamflow of up to 75% and 78% was observed in December for Gilgel Beles and Main Beles, respectively. While in the 2060s and 2080s, the largest monthly flow increase was observed in November in both subbasins.

4. Conclusions

The future climate and its impact on potential evapotranspiration and streamflow for Main Beles and Gilgel Beles subbasins are evaluated using downscaled A2 (medium-high) and B2 (medium-low) emission scenarios. The findings show a consistent increasing trend for both minimum and maximum temperature for all time horizons (2030s, 2060s and 2080s) with a higher rate of increase towards the end of the century. Results also show that the rate of change of maximum temperature is higher than the rate of change of minimum temperature. We have found out that this will be responsible for alterations of the hydrological cycle by increasing the evapotranspiration by 2% in the 2030s, 4.7% in the 2060s and 7.8% at the end of the century. The increase in evapotranspiration suggests increased crop water requirement in future crop production. Thus, the design of irrigation infrastructure should take this into account. Moreover, larger storage structure is needed to offset the decline in the rainfall of the major rainfall season. The model output indicated that this change in the water balance component could severely affect streamflow of both rivers. The average annual streamflow could decrease in future time horizons compared to the baseline period. On a seasonal bases, the wet season flow will decrease for the coming century; reducing by 19% and 17% for Main and Gilgel Beles, respectively at the end of the century. The dry season flow may increase by 64% and 65% for Main Beles and Gilgel Beles, respectively by the end of the century. The monthly and seasonal version of streamflow is relatively higher than the annual flow variation.

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Author Contributions: Abeyou W. Worqlul designed the model calibration, validation and down scaling of the climate data. Abeyou W. Worqlul, Yihun T. Dile, Essayas K. Ayana and Anwar A. Adem wrote the paper. Jaehak Jeong and Thomas Gerik supervised the research.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A:

The special report on emission scenarios (SRES)

In 1996, the IPCC began the development of new set of emission scenarios, effectively to update and replace the well-known IS92 scenarios. The approved new set of scenarios is described in the IPCC special report on emission scenarios (SRES). Four different narrative storylines were developed to describe consistently the relationship between the forces driving emission and their evaluation and to add context for the scenario quantification. The resulting set of 40 scenarios cover the wide range of the main demographic, economic and technological driving forces of the future greenhouse gas and sulfur emissions. Each scenario represents the specific quantification of one of the four storylines. All the scenarios based on the same storyline constitute a scenario "family" which briefly describe the main characteristics of the four SRES storylines and scenario family (IPCC-TGICA, 2007).

A1. The A1 storyline and scenario family describe a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: - Fossil intensive (A1FI) - Non - fossil energy sources (A1T), or - Balance across all sources (A1B) (balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline and scenario family describe a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines.

B1. The B1 storyline and scenario family describe a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describe a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection.

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