Short thesis for the degree of Doctor of Philosophy (PhD)

Impacts of climate change on water resources in the Upper Blue Nile Basin, Ethiopia

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Debrecen, 2023

1. Introduction

Climate change is indisputably a very important challenge facing the world in the 21st century due to its extensive impacts on the environment and socioeconomic situations of the global community. Although the occurrence phenomena of climate change are natural, it is unarguably believed by the scientific community that the causes of its occurrence are anthropogenic activities. Because future anthropogenic activities and greenhouse gas emissions are uncertain, it is strongly assumed that the global temperature will keep changing in the future. According to IPCC (2021), the global atmospheric temperature is expected to increase by 2.6°C to 4.8°C at the end of the 21st century under a high greenhouse gas emissions scenario (RCP8.5). A variety of climate model projections show that precipitation is very likely to increase in high latitudes and near the major convergence zones in the tropics in some seasons, while it is expected to decrease in many subtropical regions. Such changes in the intensity and distribution of rainfall will have serious implications for water resources. Currently, about one-third of the world's population lives in water-scarce countries, and by 2025, two-thirds of the world's population will face water scarcity problems as river flows and groundwater recharge decline (FAO, 2010).

Due to climate change, the frequency of severe droughts and floods is expected to increase in various regions. In Ethiopia, changes in precipitation and temperature have affected the water balance components including runoff, evapotranspiration, and groundwater storage of the major river basins over the past five decades. The dry-season hydrological drought and wet-season flooding have also become common problems in many perennial rivers. Previous studies, including Kim & Kaluarachchi (2009), Worqlul et al. (2018a), and Malede et al. (2022) indicated that the hydrological process of the headwater catchments of the upper Blue Nile basin in Ethiopia has been affected by climate change.

Lake Tana basin is the source and the upper catchment of the Blue Nile basin, which is one the resourceful area in Ethiopian due to its high potential in micro and macro water resource projects in irrigation and hydroelectric power development, livestock and fish production, production of varieties of high-value crops, recreation, and ecotourism. However, the basin is highly vulnerable and could be severely impacted by climate change due to unwise utilization of natural resources, and lack of proper adaptation and resilience measures. Even though, studies are conducted in the assessment of climate change and its impacts, most of which focused on impacts on streamflow of watersheds, limiting our understanding and making it difficult to distinguish the impact of climate change on the basin's overall water resource.

1.1. Aim and objectives of the study

The main aim of this study was to evaluate the change in climate and its impact on the water resource under the worst-case Representative Concentration Pathway (RCP) emission scenario in the headwater catchments of the upper Blue Nile basin, Ethiopia. To address the aim, the following objectives were set:

- Assessing the change in temperature and rainfall over the study area;
- Investigate the impacts of climate change on evapotranspiration and seasonal aridity of watersheds;
- Evaluate the impact of climate change on the stream flow nature of watersheds; and
- Assessing the dynamics of future hydrological extremes of watersheds in the Lake Tana basin under the high emission climate change scenario.

2. Materials and Methods

2.1. Climate and hydrological data collection and processing, and analysis

Meteorological data were obtained from Ethiopia's National Meteorological Agency. Even though, there are more meteorological stations in the study area, many of them lack adequate data and have missing values even in recorded data. The missing data were replaced by -99, which is compatible with the SWAT model, during the SWAT model calibration and validation process.

Climate model data were obtained from the Earth System Grid Federation (ESGF) website, USA. Because the majority of the meteorological stations in the watersheds do not have long-term historical recorded data for regional downscaling, Global Climate Models (GCM) were used directly after bias correction. In Coupled Model Inter-comparison Project Phase 5 (CMIP5), six Global Climate Models, including the CanESM2, EC-EARTH, CNRM-CM5, HadGEM2-ES, NORESM1-M, and CSIRO-Mk3-6-0, project precipitation, and temperature data.

For calibration and validation of the SWAT model, flow data from four watersheds (Gilgel Abay, Gumara, Ribb, and Megech) were obtained from Ethiopia's Ministry of Water and Energy (MoWE). Like meteorological data, the flow data were collected on a daily time scale, with missing values replaced by -99.

Changes in temperature and rainfall obtained from Global Climate Models (GCM) and their impacts on PET, stream flow including the extreme flow events were evaluated based on classifying the entire data into four categories. The data range consisting 1971–2000, was taken as a baseline, whereas the data ranges 2011–2040 (*Period 1*), 2041–2070 (*Period 2*), and 2071–2100 (*Period 3*) were considered as the targeted change study periods.

2.2. Geophysical data collection and processing

In addition to climatic data, the hydrological model required geophysical data such as land use/cover, soil, and altitude (DEM) (SWAT). The land use/cover data were obtained from MoWE, whereas the soil data for the study area were obtained from the FAO-UNESCO Soil Map of the World. The SRTM Digital Elevation Model (DEM) data with a resolution of 30 m*30 m were obtained from The United States Geological Survey (USGS) website.

2.3. Bias correction of Climate Models data

Climate variables such as rainfall and temperature obtained from such coarse-resolution climate models are heavily influenced by local topographies such as mountains, and local depressions. Thus, bias correction was required to minimize the deviation of climate models output from real observed data from meteorological stations, and it was accomplished using variance scaling and power transformation methods for temperature and precipitation, respectively, using the CMhyd software (Rathjens et al., 2016).

2.4. SWAT model setup and Simulation

SWAT is a semi-distributed small watershed or large river basin scale hydrological model that simulates the water balance components and sediment transport. The model begins with the watershed characterization process and proceeds through six key steps: (1) watershed delineation, (2) Hydrological Response Unit definition and analysis, (3) Climate and Weather data formation, (4) Simulation, (5) Model calibration, and (6) Model validation.

2.5. SWAT model Calibration and Validation

The model was calibrated by seven years of daily climate and stream flow data using the SWAT-CUP (SWAT-Calibration and Uncertainty Programs) version 12 software. The 11 calibrated parameters were also validated using five years of independent data in the four watersheds. The model's efficiency was assessed using statistical variables such as Nash–Sutcliffe Efficiency (NSE) and the Relative Volume Error (RVE) that determine the fitness of simulated flow with measured flow data of watersheds.

2.6. Simulation of Potential Evapotranspiration

The potential evapotranspiration of the basin is estimated based on energy balance and temperature–based methods using the Soil Water Assessment Tool (SWAT) software. SWAT model supports only three evapotranspiration estimation methods, and among those Hargreaves (HR) method is the only temperature–based method, whereas the other two methods such as Penman-Monteith and Priestley Tylor methods are energy balance methods. The Penman-Monteith (PM) method, which is commonly used and recommended by the Food and Agriculture Organization (FAO) of the United Nations (Allen et al., 1998) was used in this study. The results of these HR and PM methods were compared based on their performance in the simulation of stream flow by the SWAT model, and the best-fit method was selected and used in the change analysis of PET and aridity index.

2.7. Estimation of Aridity Index (AI)

An Aridity index (AI) is a numerical indicator of the degree of dryness of the climate at a given location. It is an index of the average water available in the soil, defined as the ratio between mean annual precipitation (P) and mean annual evapotranspiration (PET) (UNEP, 1993).

Even though according to the revised United Nations Environment Program, AI is estimated based on the mean annual precipitation and potential evapotranspiration, in this study, the formula is applied in the estimation of the seasonal aridity index of the watersheds.

2.8. Selection and analysis of high flow and low flow of watersheds

The 7-day sustained low flow selection method was used in this study to select the low flows from the daily annual flow of the entire study period. After obtaining the daily flow from the SWAT model, the entire 120 years of daily flow data were sorted from lowest to highest values of flow in the annual time frame, and the lowest 7-

days of flows in each year were selected, and the mean values of each selected flow in a year was calculated. The change in low flow was evaluated by comparing the mean values of the three periods with the baseline period data.

In the selection of high flows, the Annual Maximum Series (AMS) model was used, and by this method, one maximum flow is chosen from each year. Like, the low flow, the changes in the three periods were evaluated by comparing the mean values with the baseline period.

The change in low flow and high flows of the watersheds were also examined using Flow Duration Curves (FDCs). The change of extreme events was assessed in terms of the probability of exceedance (in the case of high flow) and non-exceedance (in the case of low flow) of each event and by classifying them into four ranges of categories (Q_0–Q_{25}, Q_{26}–Q_{50}, Q_{51}–Q_{75}, and Q_{76}–Q_{100}).

3. Scientific Results

Thesis Statement 1

I found that both the maximum temperature and minimum temperature are expected to increase in the region over the 21st century, with the highest increase in *Period 3*; whereas the change in rainfall showed seasonal fluctuation.

In monthly time scales, the highest rise in maximum temperature and minimum temperature are expected in *Period 3* with 5.17 ^{o}C and 5.42 ^{o}C, respectively, projected by the CSIRO-Mk3-6-0. Using an ensemble of six climate models, the maximum temperature is expected to rise by 1.91^{o}C, 2.40 ^{o}C, and 4.04 ^{o}C in *Period 1*, *Period 2*, and *Period 3*, respectively, whereas the minimum temperature is expected to increase by 1.57 ^{o}C, 2.75 ^{o}C, and 4.28 ^{o}C, respectively (Figure 1). All climate models predicted that rainfall changes will have a high level of inter-annual fluctuations in all periods. Rainfall is expected to increase up to 16.21%, 17.00%, and 18.56% in *Period 1*, *Period 2*, and *Period 3*, respectively. The highest rate of decreases in rainfall are 2.26%, 4.22%, and 5.66% in *Period 1*, *Period 2*, and *Period 3*, respectively. Annually, it is expected to increase by 4.43%, 4.38%, and 4.70% in *Period 1*, *Period 2*, and *Period 3*, respectively (Figure 2).

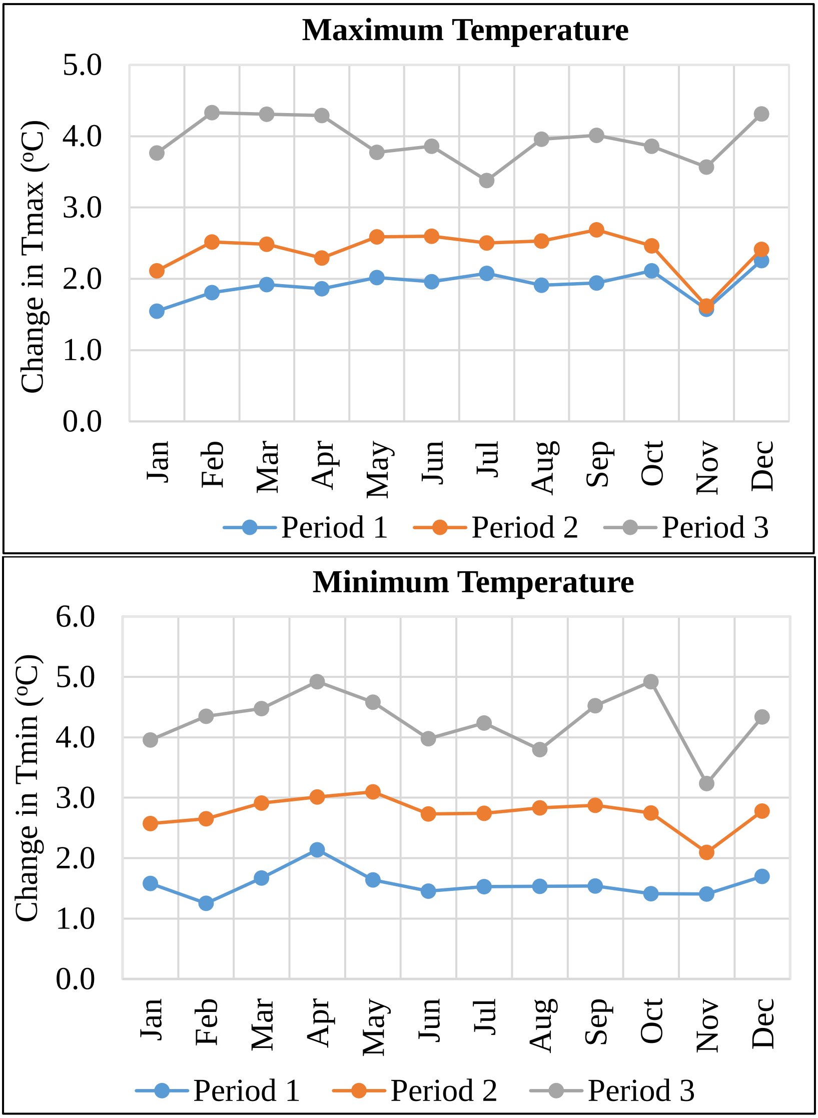

Figure 1: Change in maximum temperature in Period 1, Period 2, and Period 3 compared to the baseline period (1971-2000)

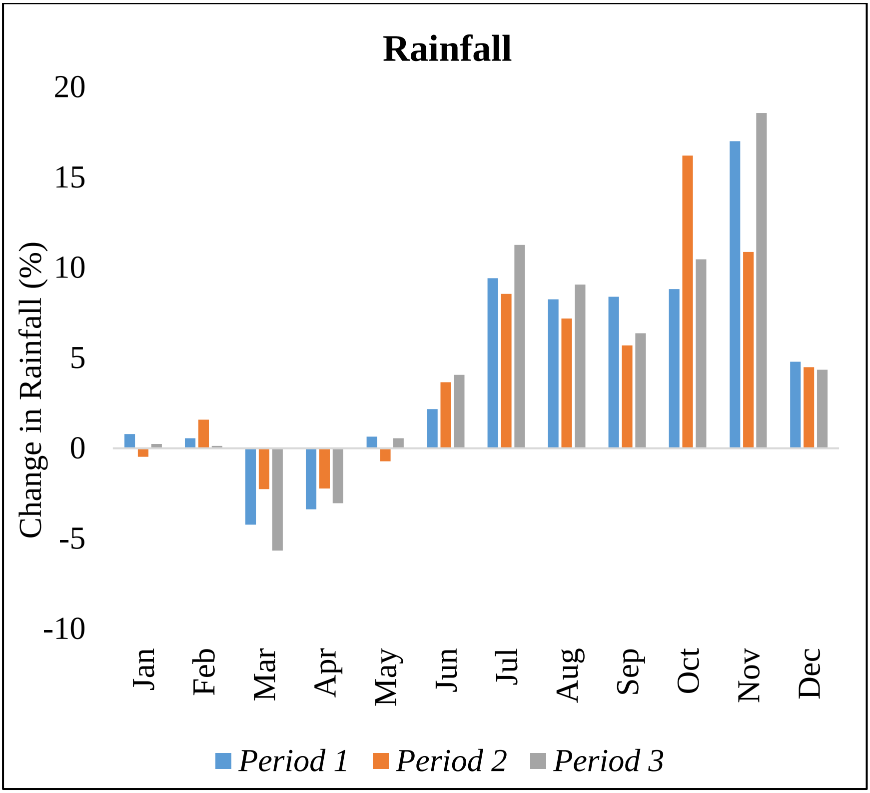

Figure 2: Change in rainfall in Period 1, Period 2, and Period 3 compared to the baseline period (1971-2000).

Thesis Statement 2

The loss of water by PET is anticipated to increase due to the increase in temperature; consequently, I also found that seasonal aridity is likely to increase prominently in the dry season.

In the last thirty years of this century, the seasonal potential evapotranspiration is expected to increase up to 24.37%, in *Period 3*. The highest changes in PET in *Period 1* and *Period 2* are likely to rise by 9.99% and 12.59%, respectively. These highest changes are in *Period 1* and *Period 3*, and are projected by CSIRO-Mk3–6–0, while in *Period 2* it is projected by CanESM2. Based on the ensemble mean monthly value of all climate models, the annual potential evapotranspiration is projected to rise by 5.56%, 8.25%, and 13.92% in *Period 1*, *Period 2*, and *Period 3*, respectively. The highest increasing changes in Aridity Index in *Period 1*, *Period 2*, and *Period 3* are 0.084, 0.158, and 0.263, respectively, whereas, the highest decreasing changes are 0.081, 0.179, and 0.285, respectively based on the ensemble mean monthly value of all climate models. The decrease in AI is expected to be observed between December and May.

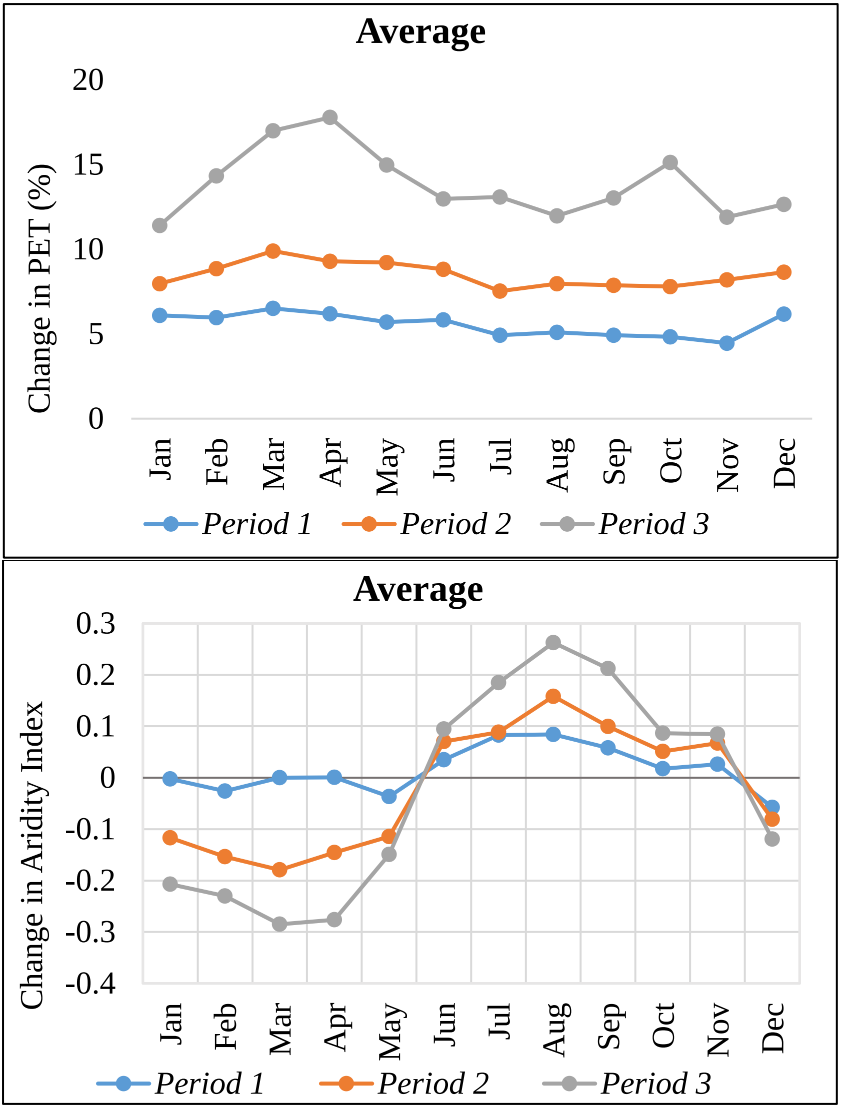

Figure 3. Change in PET and Aridity Index in Period 1, Period 2, and Period 3 compared to the baseline period (1971-2000)

Thesis Statement 3

I revealed that future climate change is expected to alter the stream flow nature of watersheds, with an increase in rainy/summer and post-summer seasons, and a decrease in dry season.

The highest change in stream flow in all watersheds is expected in Period 3, with increases of 27.81%, 27.47%, 26.47%, and 24.97% in the Ribb, Gilgel Abay, Gumara, and Megech watersheds, respectively. Except for the Ribb watershed which is predicted by CNRM-CM5, these highest increments in the other three watersheds were projected by the CanESM2 climate model. Though seasonal fluctuations are expected, the highest monthly rate of change in stream flow based on the ensemble means of all climate models in Gilgel Abay, Gumara, Ribb, and Megech watersheds is 13.29%, 16.11%, 13.08%, and 14.87%, respectively (Figure 4 and 5). Annually, the change in stream flow in the Gilgel Abay, Gumara, Ribb, and Megech watersheds in *Period 1*, *Period 2*, and *Period 3* increased by 2.94%, 2.84%, and 2.55%; 3.01%, 3.00%, and 3.57%; 2.82%, 2.84%, and 3.79%; and 2.75%, 3.13%, and 3.14%; respectively.

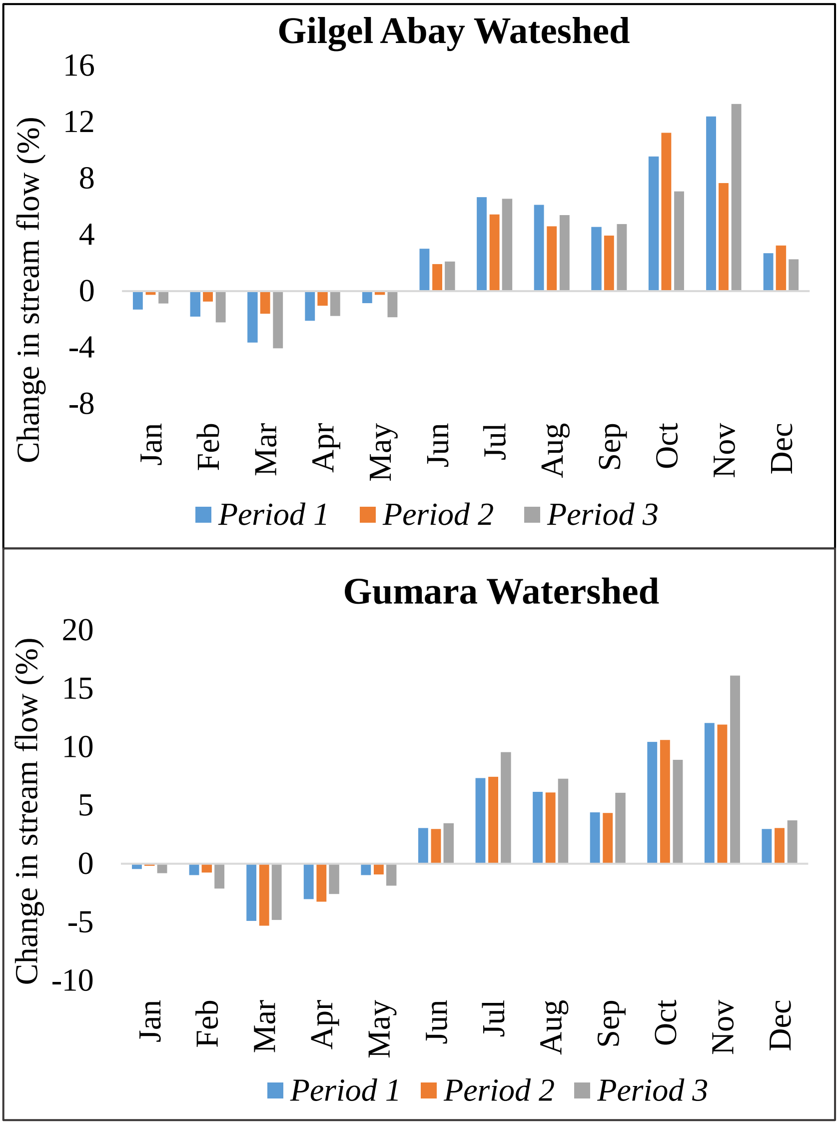

Figure 4. Change in stream flow in Gilgel Abay and Gumara watersheds in Period 1, Period 2, and Period 3 compared to the baseline period.

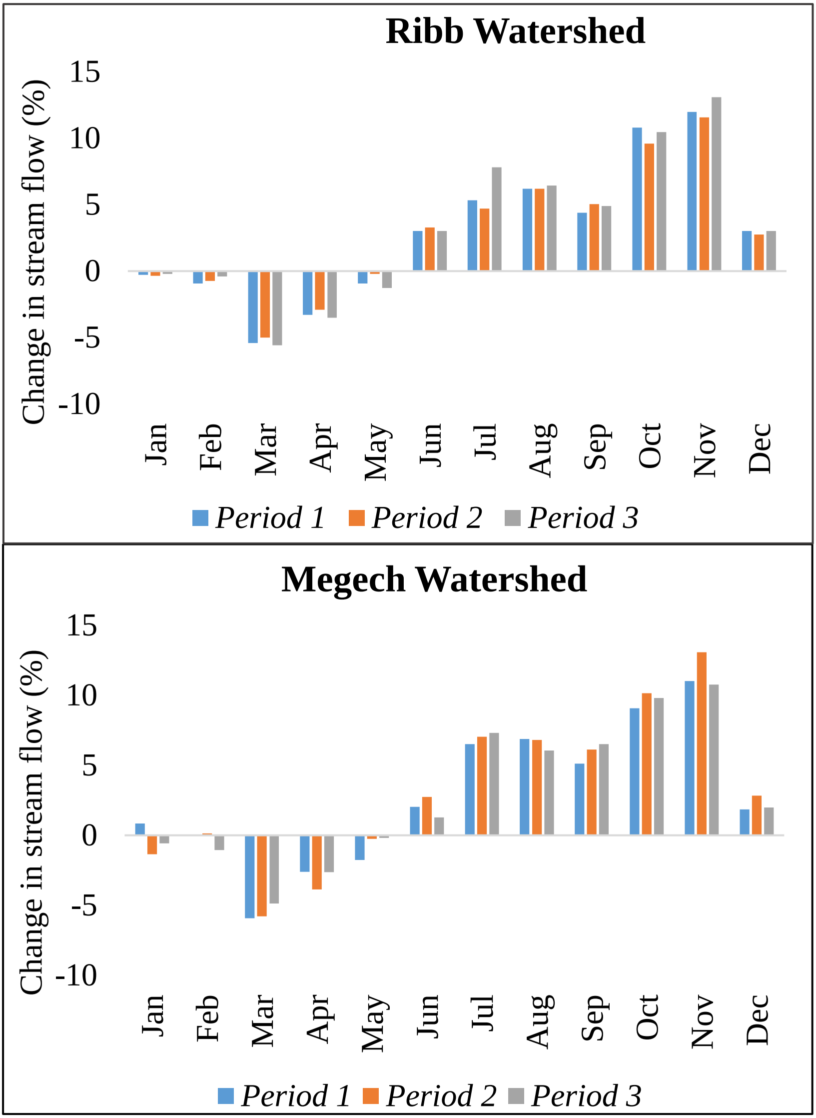

Figure 5: Change in stream flow in Ribb and Megech watersheds in Period 1, Period 2, and Period 3 compared to the baseline period.

Thesis Statement 4

I discovered that the low flows of watersheds are anticipated to exhibit a consistent decline throughout the 21st century, whereas the high flow events are expected to increase across all watersheds.

The low flow is expected to consistently decrease in all watersheds over all periods, with a maximum decrease of 12.31%, 11.71%, 10.49%, and 6.8% in the Ribb, Gumara, Megech, and Gilgel Abay watersheds, respectively in *Period 3* (Table 1). The high flow of all watersheds is expected to increase prominently in *Period 3,* which is 22.12%, 18.67%, 17.69%, and 14.36% in the Megech, Ribb, Gilgel Abay, and Gumara watersheds, respectively (Table 2). Based on the FDCs, the low flows of Gilgel Abay and Megech watersheds are likely to increase in the Q_0-Q_{25} and Q_{26}-Q_{50} whereas in the Gumara and Ribb watersheds, it is expected to decrease in all non-exceedance probability categories. The rate of change in high flow in terms of FDCs showed increasing pattern in all exceedance probability categories with the highest rate of increasing change in the last category (Q_{76}-Q_{100}) in Gilgel Abay, Gumara, and Megech watersheds, whereas in Ribb watershed, the highest rate of change is expected in the first category (Q_0-Q_{25}).

Table 1: Change in the low flow of watersheds

Watersheds	Average low flow in the baseline period (m^3/s)	Change in low flow (%)		
		2020s	2050s	2080s
Gilgel Abay	2.45	–3.67	–5.31	–6.8
Gumara	0.69	–4.71	–8.51	–11.71
Ribb	0.40	–5.30	–7.57	–12.31
Megech	1.02	–1.45	–6.69	–10.49

Table 2: Change in the high flow of watersheds.

Watersheds	Average high flow in the baseline period (m^3/s)	Change in high flow (%)		
		2020s	2050s	2080s
Gilgel Abay	283.49	10.56	13.57	17.69
Gumara	238.1	7.15	11.18	14.36
Ribb	94.53	3.56	8.50	18.67
Megech	87.10	6.72	10.63	22.12

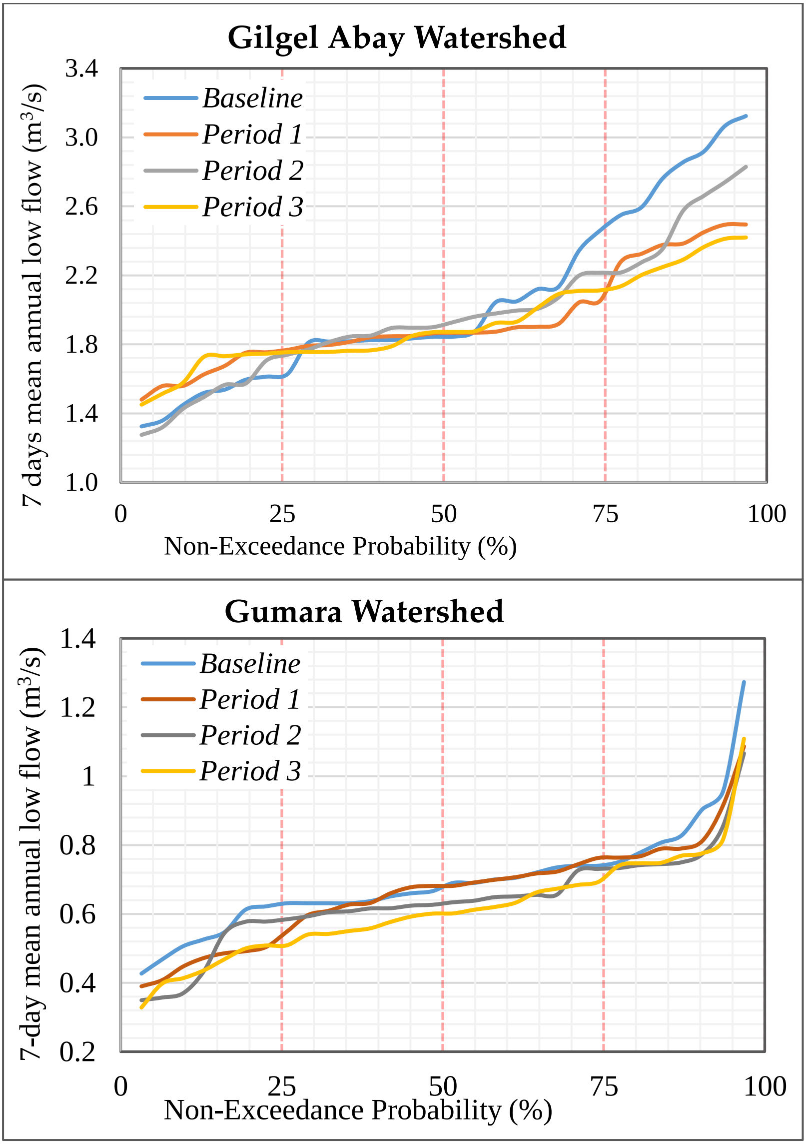

Figure 6. Flow Duration Curves of low flow of Gilgel Abay and Gumara watersheds

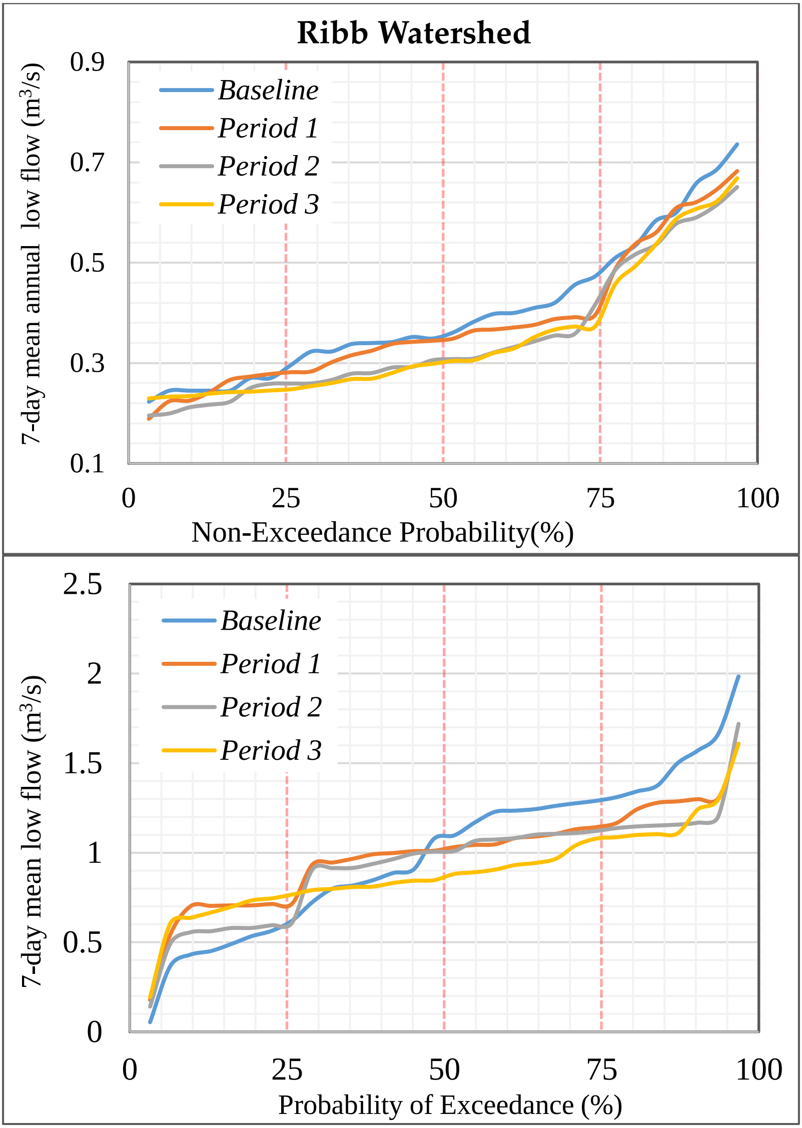

Figure 7. Flow Duration Curves of low flows in Ribb and Megech watersheds

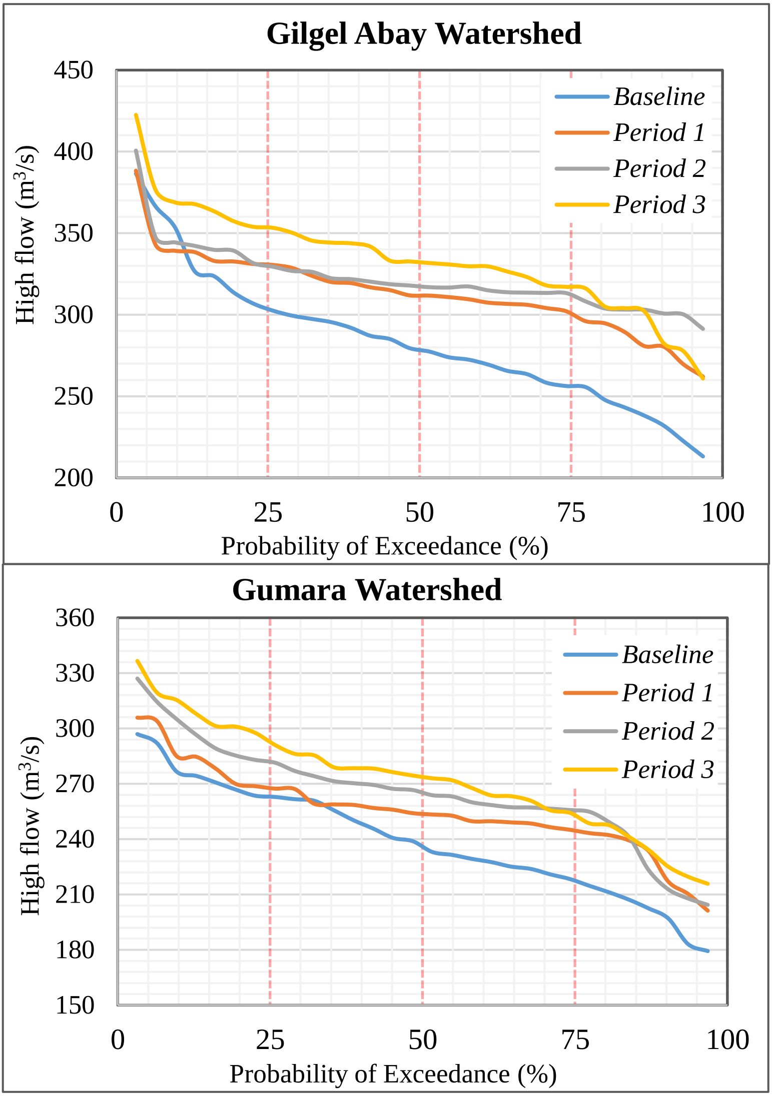

Figure 9. Flow Duration Curves of high flows in Gilgel Abay and Gumara watersheds

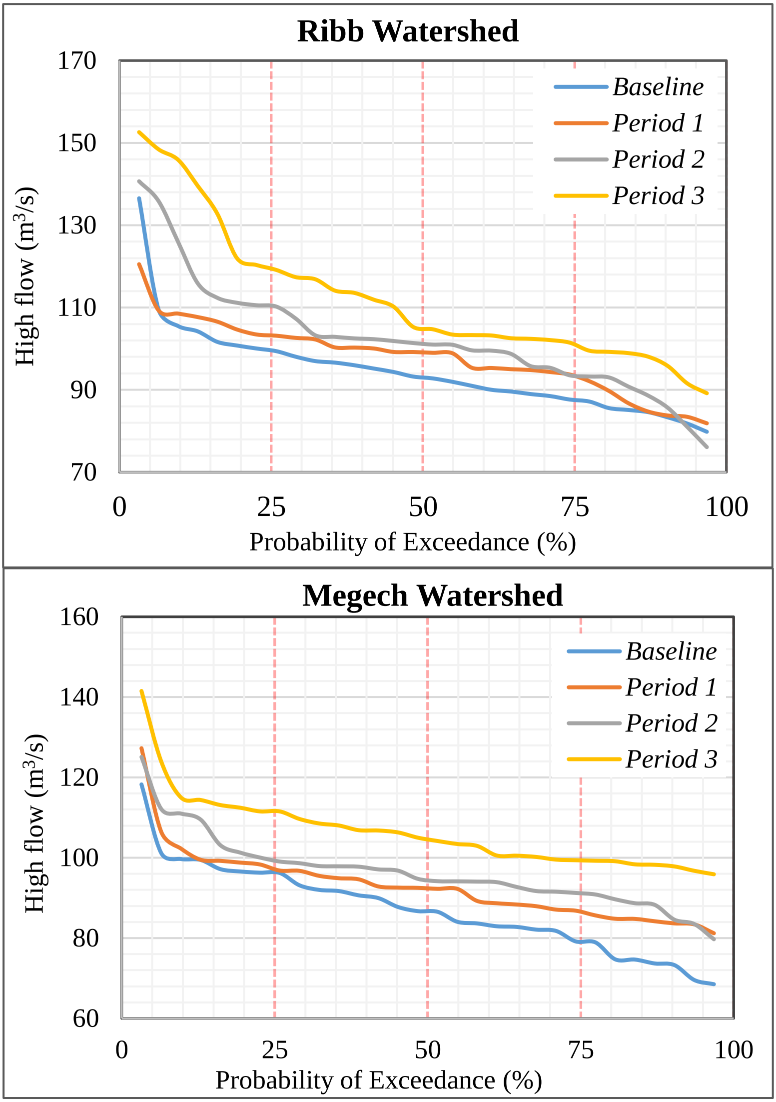

Figure. 8: Flow Duration Curve of High flows of Ribb and Megech watersheds

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Subject: PhD Publication List

Candidate: Gashaw Gismu Chakilu
Doctoral School: Doctoral School of Earth Sciences
MTMT ID: 10088057

List of publications related to the dissertation

Foreign language scientific articles in international journals (3)

1. **Chakilu, G. G.**, Szegedi, S., Túri, Z.: The Dynamics of Hydrological Extremes under the Highest Emission Climate Change Scenario in the Headwater Catchments of the Upper Blue Nile Basin, Ethiopia.
   Water. 15 (2), 1-20, 2023. EISSN: 2073-4441.
   DOI: http://dx.doi.org/10.3390/w15020358
   IF: 3.53 (2021)
2. **Chakilu, G. G.**, Szegedi, S., Túri, Z., Phinzi, K.: Climate change and the response of streamflow of watersheds under the high emission scenario in Lake Tana sub-basin, upper Blue Nile basin, Ethiopia.
   J Hydrol-Reg Stud. 42, 1-16, 2022. ISSN: 2214-5818.
   DOI: http://dx.doi.org/10.1016/j.ejrh.2022.101175
   IF: 5.437 (2021)
3. **Chakilu, G. G.**, Szegedi, S., Túri, Z.: Change in Stream Flow of Gumara Watershed, upper Blue Nile Basin, Ethiopia under Representative Concentration Pathway Climate Change Scenarios.
   Water. 12 (11), 1-14, 2020. EISSN: 2073-4441.
   DOI: http://dx.doi.org/10.3390/w12113046
   IF: 3.103

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List of other publications

Foreign language scientific articles in international journals (1)

4. Melash, A. A., Bogale, A. A., Migbaru, A. T., **Chakilu, G. G.**, Percze, A., Ábrahám, É. B., Mengistu, D. K.: Indigenous agricultural knowledge: A neglected human based resource for sustainable crop protection and production.
   Heliyon. 9 (1), 1-9, 2023. EISSN: 2405-8440.
   DOI: https://doi.org/10.1016/j.heliyon.2023.e12978
   IF: 3.776 (2021)

Total IF of journals (all publications): 15,846
Total IF of journals (publications related to the dissertation): 12,07

The Candidate's publication data submitted to the iDEa Tudóstér have been validated by DEENK on the basis of the Journal Citation Report (Impact Factor) database.

24 April, 2023