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Assessment of surface runoff response to climate change in a Weyib Watershed using the WeSpass-M model

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Abstract

Comprehending the impact of climate change on surface runoff is imperative to safeguard against excessive inundation vulnerability and management. This study estimates climate change effects on surface runoff using an ensemble of five climate models and the WetSpass-M model for the baseline period (1986 to 2015), mid-term (2031 to 2060), and long-term (2071 to 2100) periods. The downloaded climate models (CNRM-CM5, GFDL-ESM2M, IPSL-CM5A-MR, MPI-ESM-LR, and NorESM1-M) were downscaled by a dynamic downscaling technique and bias corrected by linear scaling. The model performance statistical indices, such as R^2 (0.90 and 0.85), NSE (0.95 and 0.89), and RMSE (4.19 and 9.94), were obtained by comparing the WetSpass-M model and filtered baseflow and direct runoff, respectively. The mean rainfall and temperature are projected to increase compared to the baseline period. The overall average monthly runoff has been rising with 8.70%, 18.22%, 6.53%, and 36.09% for RCP4.5 (MidT4.5) for the mid-term, RCP4.5 (LongT4.5) for the long-term, RCP8.5 (MidT8.5) for the mid-term, and RCP8.5 (LongT8.5) for the long-term, respectively. Seasonally, surface runoff is projected to increase throughout the entire season, except for autumn. Autumn season's surface runoff is projected to drop by 23.56%, 38.85%, 29.12%, and 43.02% for MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively. Annually, surface runoff will increase by 8.3%, 31.20%, 1.80%, and 49.30% for the MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively. Moreover, the findings conclusively underscored a dramatically rising surface runoff due to climate change, causing inundation in central and downstream watershed areas. Therefore, this increasing surface runoff will potentially affect daily life and weaken agricultural productivity; thus, reforestation and water conservation measures are required to lessen the adverse effects.

Keywords: Climate Change, CORDEX, GCM, RCP, Surface Runoff, WetSpass-M model

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1. Introduction

The term ‘climate change’ refers to variations in rainfall and temperature from historical climate patterns (Fita & Abate, 2022; Asgari et al., 2025). Climate change is one of the top global challenges and a critical crisis in the twenty-first century (Abdule et al., 2024; Sheikhroodi et al., 2024; Babaei et al., 2025). The main driving factors of climate change were anthropogenic and natural activities (Merga et al., 2022; Balcha et al., 2023). Increasing concentration of global greenhouse gases causes fluctuations in temperature, rainfall, evaporation, and water levels (Alehu & Bitana, 2023; Mummed & Seleshi, 2024). These rising temperatures and precipitation unpredictability would disrupt the hydrological cycle, decreasing ice, rising sea levels, and altering water balance (Gurara et al., 2023). For instance, according to the Intergovernmental Panel on Climate Change (IPCC) reports, global temperatures will be projected to rise dramatically in a considerable amount (IPCC, 2001; IPCC, 2021). Furthermore, climate change will lead to extreme weather events, affecting the environment, human well-being, and water resources availability (Ayalew et al., 2022). Developing continents like Africa have frequently faced climate change effects, with inadequate facilities to lessen the effects of hydrological extremes, while its economy also heavily relies on rain-fed agriculture (Daba & You, 2020; Ayalew et al., 2022; Nyembo et al., 2022; Mengistu et al., 2025). Sub-Saharan Africa’s water resources are facing an unpredictable drop in quantity and quality, posing challenges to hydrological processes and ecosystems (Nyika & Dinka, 2023).

Ethiopia has a diverse climate and agro-ecological zones that pose considerable challenges in the availability of spatiotemporal water resources and food security (Afessa & Yosef, 2019; Gebul, 2021; Taye et al., 2021). Even though Ethiopia is referred to as “East Africa's Water Tower,” it is experiencing substantial spikes in water stress and spatiotemporal water resources availability (Arsano & Tamrat, 2005; Aredo et al., 2023a; Aredo et al., 2023b). Climate change is challenging Ethiopia's agricultural-led development plan, which seeks to transform into an industrialized state by intensifying irrigation activities (Awulachew et al., 2007; Dejenie & Kakiso, 2023; Dinsa & Nurhusein, 2023). Additionally, Ethiopia's hydrological process was affected mainly by human and natural activities (Molla et al., 2019; Dile et al., 2020; Dong et al., 2022; Hordofa et al., 2023; Gebremichael & Mechal, 2025). In this country, the highest percentage of surface runoff originates from highlands and mountainous areas, while the pattern is being altered due to climate change (Ayele et al., 2016; Gebremeskel & Kebede, 2018; Shiferaw et al., 2018; Mengistu et al., 2025). Meanwhile, future climate change is projected to increase water scarcity risk and undermine the operation of hydraulic structures (Shiferaw et al., 2018; Daba & You, 2020). In comparison to the historical period, runoff has been drastically changing in Ethiopia’s numerous river basins (Shiferaw et al., 2018; Daba & You, 2020; Worku et al., 2021; Fita & Abate, 2022). For instance, surface runoff has drastically risen in the Awash and Genale Dawa, while declining at the Blue Nile and Wabe Shebele river basins (Ayele et al., 2016; Shiferaw et al., 2018; Bekele et al., 2019; Abdule et al., 2024).

Weyib watershed is located in highly varied in terms of climate, topography, agro-ecological zones, and hydrological services (Gashaw et al., 2023; Wubaye et al., 2023; Aredo et al., 2024a; Aredo et al., 2024b). Compared to Ethiopia’s Rivers, the Weyib watershed has received less research attention, despite experiencing extreme hydrological events (namely flood and drought) and a spike in water demand (Awulachew et al., 2007; NDRMC, 2020; Aredo et al., 2021a; Mengistu et al., 2022). These hydrological extremes have varied considerably throughout the spatiotemporal scale. For instance, the basin’s highland and central areas have been frequently affected due to floods and high magnitude surface runoff, causing traffic congestion (Awulachew et al., 2007; Tessema et al., 2020; NDRMC, 2020; Aredo et al., 2021a). Also, the downstream areas have been facing significant prolonged drought in numerous districts (Awulachew et al., 2007; Mengistu et al., 2022; Abebe et al., 2024). In addition, the study's outcomes have proven that surface runoff causes traffic blockage and disrupts road connections in the watershed

(Aredo et al., 2021a; Aredo et al., 2021b). Increasing surface runoff was observed throughout the point-level estimation by ensembling three climate models in the watershed (Serur & Sarma, 2018). These hydrological extremes may occur due to alterations of projected precipitation and temperatures, with considerably varied rainfall (Awulachew et al., 2007; Serur, 2020; Bulti & Abegaz, 2024). Ensembling a limited number of climate models will lead to uncertainties while projecting the climate change effects (Nannawo et al., 2022a; Nannawo et al., 2022b). However, the amount of surface runoff on a spatiotemporal scale has not been estimated so far, based on numerous climate models in the Weyib watershed.

The WCRP-generated Coordinated Regional Climate Downscaling Experiment (CORDEX), the regional climate models (RCMs) are produced by finer resolution, enabling detailed future climate variables such as temperature and rainfall (Balcha et al., 2023). The RCMs' data quality can be improved owing to spatial variability and historical climate data accuracy; hence, robust climate bias adjustment is imperative to produce reliable results (Alehu & Bitana, 2023; Mummed & Seleshi, 2024). Climate model data for hydrologic modelling (CMhyd) is an outperforming tool for downsizing downloaded data and correcting climate bias (Nannawo et al., 2022a; Nannawo et al., 2022b). These adjusted climatic data were used to forecast climate change's impact on surface runoff in the watershed. Furthermore, examining climate change effects using hydrological models was instrumental in conceptualizing and projecting future changes in water balance components with limited resources and time (Shiferaw et al., 2018; Demissie et al., 2023). The WetSpass-M model is one of the physically-based distributed hydrological models that performs well in assessing the impact of climate change on a spatiotemporal scale (Nannawo et al., 2022a; Nannawo et al., 2022b; Aredo et al., 2024a). The WetSpass-M model integrates numerous spatiotemporal input datasets to estimate water balance components, such as climate, land use, soil texture, slope, DEM, and groundwater level data. This study is unique in ensembling numerous climate models and testing a hydrological WetSpass-M model by collecting both primary and secondary data to enhance the quality of output on a spatiotemporal scale in the data-scarce watershed. The objective of this study is to estimate the effect of climate change on spatiotemporal surface runoff in the Weyib watershed by ensembling the five climate models (CNRM-CM5, GFDL-ESM2M, IPSL-CM5A-MR, MPI-ESM-LR, and NorESM1-M) and the verified WetSpass-M model.

2. Materials and Methods

2.1. Study area

The Weyib watershed is situated within 6.83°N and 7.46°N latitude and 39.53°E and 40.50°E longitude, covering an enormous agro-ecological region covering 3,611km² (Fig. 1). The maximum height is within the vicinity of Bale Mountains National Park (4346m), and it gradually decreases as it approaches the outlet of the watershed at 1739m above mean sea level. In the baseline period, the study area's mean annual peak was 22.23°C and minimum temperatures were 7.28°C (Aredo et al., 2023a; Aredo et al., 2023b). The study region features a bimodal precipitation pattern, with a mean annual precipitation ranging from 851 to 1341.23mm. The Shaya, Tegona, and Tebel Rivers are the major tributaries of the Weyib River (Aredo et al., 2024a).

2.2. Model description

The WetSpass-M model is a freely accessible, physically-based, distributed hydrological model that performs efficiently when estimating spatiotemporal water balance components (Batelaan & De Smedt, 2007; Abdollahi et al., 2017; Gelebo et al., 2022; Aredo et al., 2024a). This hydrological model estimates water balance components at raster cell scale over impermeable, vegetated, bare, and open water fractions (Eqs. 1 to 3). The model expresses thirty-four land use types in terms of vegetated, bare, open water, and impermeable areas in its lookup table (Zeabraha et al., 2020; Demissie et al., 2023; Aredo et al., 2024a).

$$ET_{raster} = a_v ET_v + a_s E_s + a_i E_i + a_o E_o \quad (1)$$

$$S_{raster} = a_v S_v + a_s S_s + a_i S_i + a_o S_o \quad (2)$$

$$R_{raster} = a_v R_v + a_s R_s + a_i R_i + a_o R_o \quad (3)$$

Where ET_{raster} is evapotranspiration, S_{raster} is runoff, R_{raster} is recharge, and E is evaporation, for each having (v) vegetated, (s) bare, (o) open water, and (i) impervious area. a_v, a_s, a_o, and a_i were fractions of vegetated, bare, open water, and impervious area, respectively.

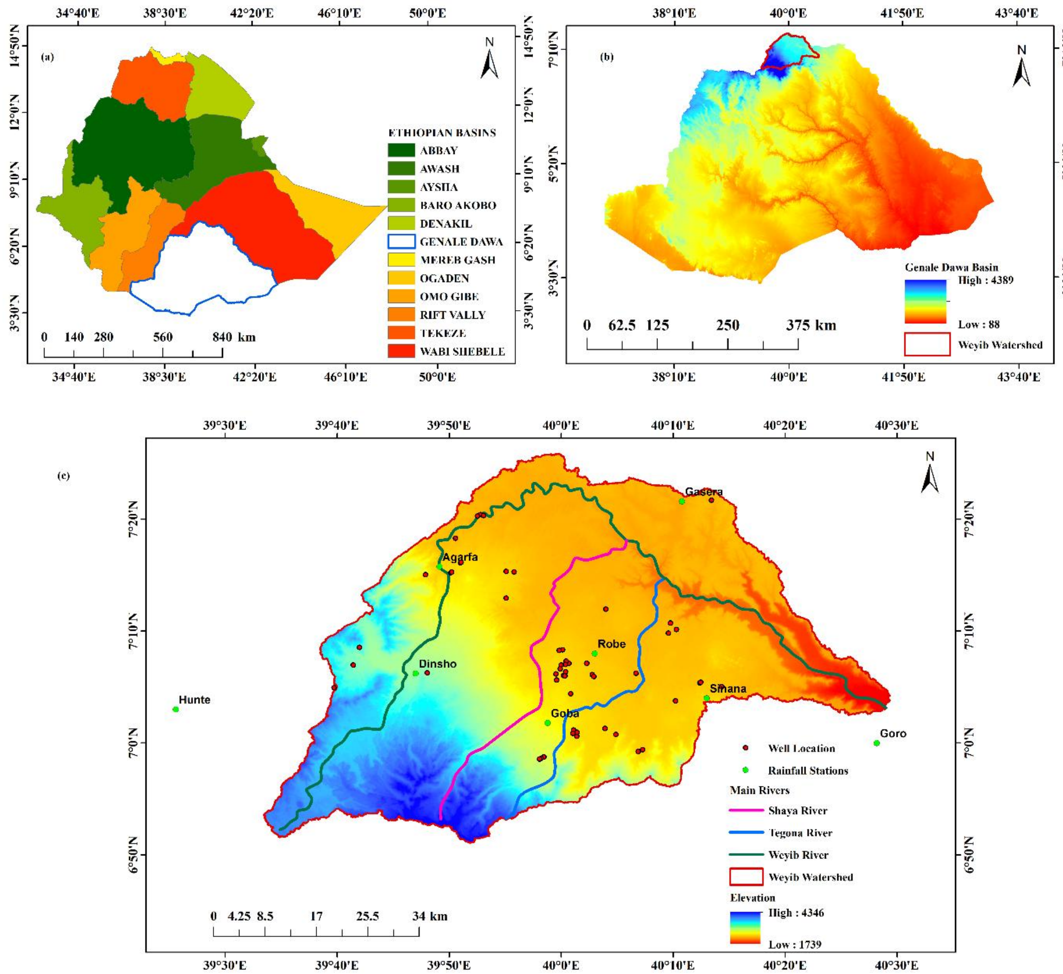

Figure 1. Location (a) Ethiopian River Basin, (b) Genale-Dawa Basin, (c) Weyib watershed

2.3. Data used and analysis

To conduct this study, primary and secondary data were collected from numerous sources, such as field measurement of groundwater levels, climate, streamflow, soil texture, digital elevation model (DEM), and land use/land cover (LULC) from various sources (Table 1). This study filled a missing dataset by Inverse distance weighting with input data from nearest stations (Hadi & Tombul, 2018; Pirani & Modarres, 2020). Studies underscore the efficiency of interpolation techniques by considering the distance between two locations (Wu & Hung, 2016; Gelebo et al., 2022). Furthermore, this study developed a linear regression equation relating to the upstream and Alemkerem gauging stations to fill in the missing streamflow data.

Table 1. Data collected for this study

No	Data Type	Resolution	Sources
1	Historical climate data	1986 to 2015	National Meteorology Agency, Ethiopia
2	Stream flow	1986 to 2015	Ministry of Water and Energy, Ethiopia
3	LULC	30 × 30m	Landsat 8 OLI/TIRS
4	Soil texture	30 × 30m	Ethiopian Ministry of Agriculture and FAO
5	DEM	30 × 30m	USGS Earth Explorer

2.4. Climate model selection and analysis

Projected climate change data, such as precipitation and temperature, were downloaded from the WCRP official website in NetCDF format from the Coordinated Regional Climate Downscaling Experiment (CORDEX) for the baseline (1986–2015), mid-term (2031–2060), and long-term (2071–2100) periods using RCP4.5 and RCP8.5 scenarios. Based on data accuracy and efficiency, this study chose five GCMs (CNRM-CM5, GFDL-ESM2M, IPSL-CM5A-MR, MPI-ESM-LR, and NorESM1-M models) to evaluate climate change effects on the study area (Worku et al., 2021; Ayalew et al., 2022; Nannawo et al., 2022a; Mengistu et al., 2023; Shigute et al., 2024). Methodologically, this study used downscaled climate data by a dynamic downscaling technique, and available biases were corrected by linear scaling (multiplicative) for precipitation and linear scaling (additive) for temperature using Climate Model data for hydrologic modeling (CMhyd) (Nannawo et al., 2022a; Nannawo et al., 2022b).

2.5. WetSpass-M model input data

This model was developed based on two primary input categories: geospatial and lookup tables for land-use and soil texture. A hydro-climate dataset includes baseflow, direct-runoff, static water level, rainfall, wind speed, temperature, and potential evapotranspiration (PET). To overcome the study area's groundwater levels data limitation, a deep meter was used to gauge the depth to the static groundwater level in fifty-three boreholes over the primary wet season (late July to August) and the dry season (late November to December) in 2022. Spatial data of biophysical basin characteristics of the watershed are presented in Figures 2a to 3b. The LULC map was classified into six main categories as presented in Fig. 3b. Additionally, the soil texture in the study area was categorized into four classes as presented in Fig. 3a. This spatial data was prepared in an ASCII file format with equal cell sizes. Furthermore, the WetSpass-M model performance was verified by separating streamflow into baseflow and direct runoff.

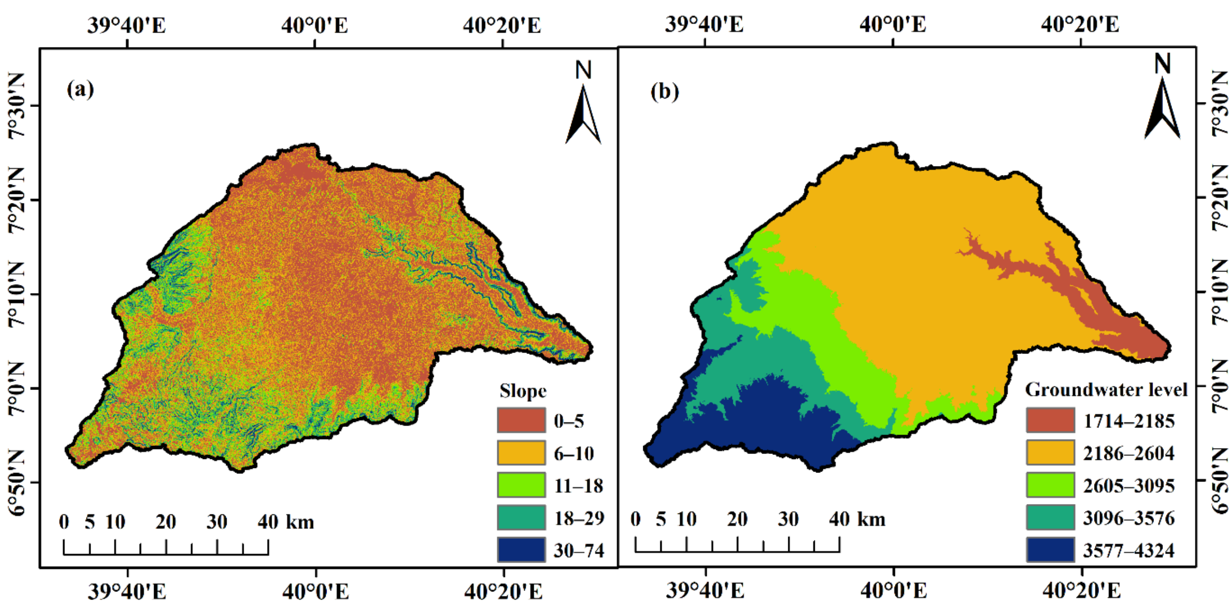

Figure 2. (a) Slope (%) and (b) mean groundwater level (meters) maps

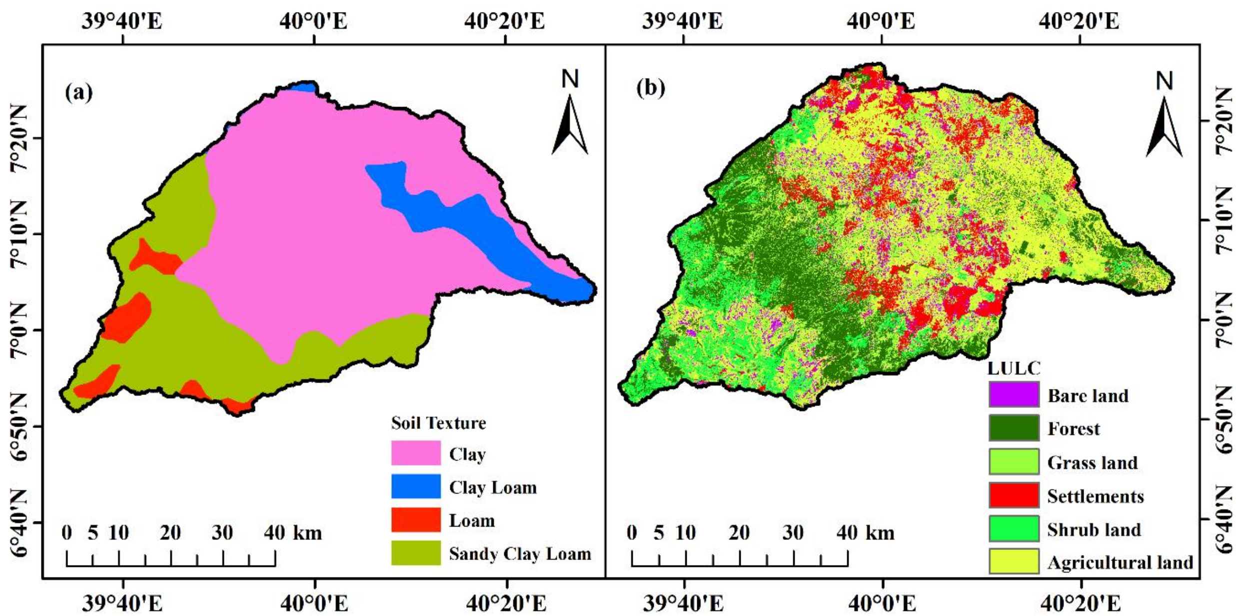

Figure 3. (a) Soil texture and (b) LULC maps

2.6. Model performance evaluation

The WetSpass-M model estimation capability was evaluated by comparing filtered baseflow and direct runoff to corresponding values using the statistical indices such as Nash-Sutcliffe Efficiency (NSE), Coefficient of Determination (R^2), and Root Mean Square Error (RMSE), as depicted in Eqs. 4 and 5 (Aredo et al., 2023a; Aredo et al., 2023b).

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \overline{P})^2}}\right]^2 \quad (4)$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2}\right] \quad (5)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \quad (6)$$

where O_i is observed data at i^{th}, P_i is model simulated at i^{th}, $\overline{O}$ is the observed mean, $\overline{P}$ is the simulated mean, and n is the number of datasets used.

2.7. Baseflow separation

This study used IHACRES to divide the streamflow into baseflow and direct runoff, based on its performance in the study area (Aredo et al., 2024a). The IHACRES filter technique was used to separate streamflow into baseflow and direct runoff (Eq. 6).

$$BF_t = \frac{k}{1+C}BF_{t-1} + \frac{C}{1+C}(Q_t + \alpha_q Q_{t-1}) \quad (7)$$

Where Q_{t-1} is initial streamflow for the preceding sampling to t; Q_t is initial streamflow for t^{th} sampling; BF_t is filtered baseflow response for t^{th} sampling; C is a shape parameter for separation and altered; k is a filter parameter given by the recession constant; $BF_{(t-1)}$ is filtered baseflow response for the preceding sampling to t; and α_q are filter parameters.

2.8. Methodological flowchart

To achieve the study's objective, an overall conceptual methodological framework was developed to collect primary and secondary data from numerous sources, the hydrological WetSpass-M model, and ensembling multi-climate models to mitigate over- or underestimating single models. This study uses the WetSpass-M hydrological model with modeling preparation, performance evaluation, and verification by historical climate data; then it uses ensemble climate models to project spatiotemporal surface runoff for the study area. Fig. 4 depicts a methodological flowchart for this study.

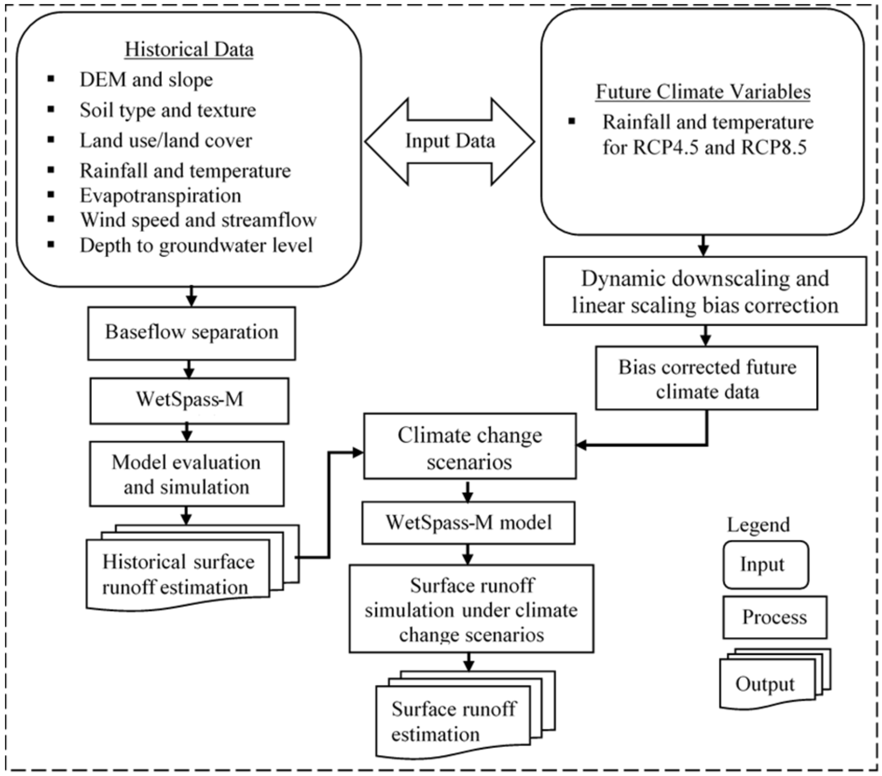

Figure 4. Conceptual framework of the study

3. Results and Discussions

3.1. Analysis of projected climate

The ensemble mean monthly temperature is projected to rise considerably in comparison to the baseline period (Fig. 5). The mean monthly temperature is likely to rise by 0.90°C, 1.65°C, 1.47°C, and 3.58°C for MidT4.5, LongT4.5, MidT8.5, and LongT8.5 scenarios, respectively. Compared to the baseline period (14.16°C), the lowest rise in monthly temperature will be expected in September by amounts of 0.63°C, 1.10°C, 1.08°C, and 3.00°C for MidT4.5, LongT4.5, MidT8.5, and LongT8.5 scenarios, respectively. Furthermore, compared to the baseline period (14.23°C), the highest spikes in monthly temperature will be 1.29°C for MidT4.5 and 2.40°C for MidT8.5, and occur in February. Unlike RCP4.5, the maximum rise in monthly temperature will be experienced in January by 4.43°C for MidT8.5 and in April by 2.12°C for LongT8.5.

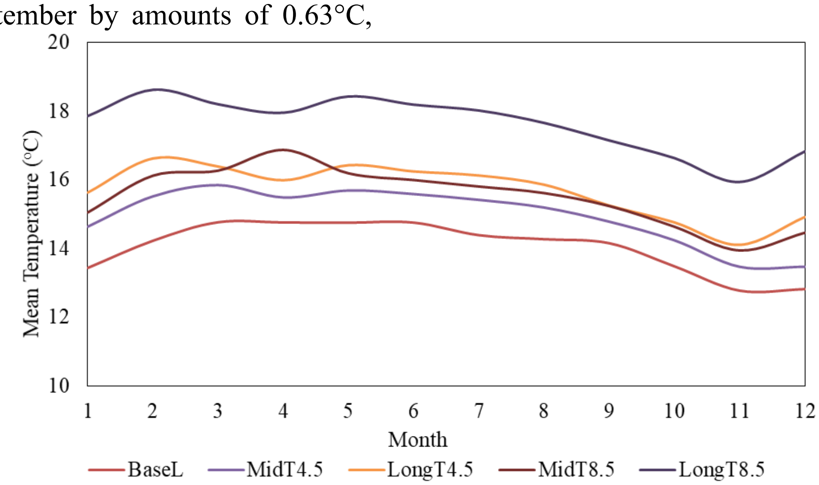

Figure 5. Mean monthly temperature for the watershed. Note: BaseL: Baseline period, MidT4.5: Mid-term for RCP4.5, LongT4.5: Long-term for RCP4.5, MidT8.5: Mid-term for RCP8.5, and LongT8.5: Long-term for RCP8.5.

Compared to the baseline period, the study area will receive significantly rising rainfall during the RCP4.5 and RCP8.5 climate change scenarios. For instance, compared to the baseline period (1002.84mm/year), the estimated mean annual rainfall for MidT4.5, LongT4.5, MidT8.5, and LongT8.5 will rise notably by 74.37mm (7.42%), 144.87mm (14.45%), 67.32mm (6.71%), and 231.49mm (23.08%), respectively (Fig. 6). Comparable to baseline period, the peak monthly rainfall was recorded in April with amount of 143.17mm, 193.74mm, 225.27mm, 192.11mm, and 229.82mm per month for corresponding the baseline period, MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively. However, the highest percentage rise in monthly rainfall will be recorded in March for MidT4.5, LongT4.5, and MidT8.5 by 65.14%, 148.11%, and 63.66%, respectively, whereas LongT8.5 (203.67%) will be in February. In November, the highest percent decline of mean monthly rainfall will be recorded by 27.52%, 43.65%, 33.70%, and 25.23% for MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively. The study area will generally receive a considerably increasing overall mean monthly rainfall by 11.06mm, 21.15mm, 9.85mm, and 36.35mm for MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively.

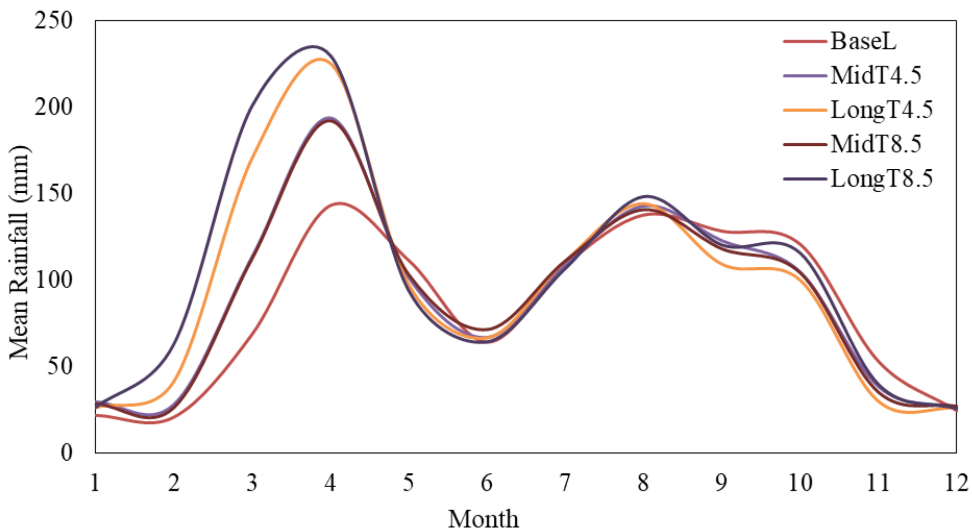

Figure 6. Mean monthly rainfall for the watershed.

Climate change and variability analysis is instrumental in boosting the management and availability of reliable water resources (Nannawo et al., 2022a; Nannawo et al., 2022b). Compared to the baseline period, the projected mean temperature and precipitation increased during both RCP4.5 and RCP8.5 in the watershed (Figs. 5 and 6). This analysis output fell precisely within a comparable range to the outcomes of existing climate change studies in Ethiopia. For instance, research undertaken across the Genale-Dawa river basin in some watersheds demonstrated an enormous spike in predicted temperature and rainfall (Negewo & Sarma, 2021; Abdule et al., 2023; Mustefa & Muluneh, 2024). Specifically, using three climate models, rainfall and temperature had increased in the watershed (Serur & Sarma, 2018). Likewise, the watershed, the annual temperature had increased in the Bilate sub-basin (Nannawo et al., 2022a; Nannawo et al., 2022b). Furthermore, annual temperature and precipitation have increased drastically in the Rift Valley lake basin, Ethiopia (Balcha et al., 2023). Contrary to various analyses, projected annual rainfall will rise over a prolonged period while falling over the short run during both RCPs (Mummed & Seleshi, 2024). Furthermore, numerous studies have demonstrated that, under both the RCPs, climate change would cause rainfall and temperature to go up significantly in the decades ahead (Getachew & Manjunatha, 2022; Alehu & Bitana, 2023; Balcha et al., 2023).

3.2. WetSpass-M model evaluation

The model performance was verified by comparing the WetSpass-M model with its corresponding results to filtered baseflow and direct runoff, respectively (Fig. 7). The model performance evaluation resulted in R^2 (0.90 and 0.85), NSE (0.95 and 0.89), and RMSE (4.19 and 9.94) by comparing the WetSpass-M model and filtered baseflow and direct runoff, respectively. Comparable model efficiency was recorded in various diverse settings and climate change effects assessments (Molla et al., 2019; Ashaolu et al., 2020; Nannawo et al., 2022; Demissie et al., 2023; Aredo et al., 2024a; Aredo et al., 2024b).

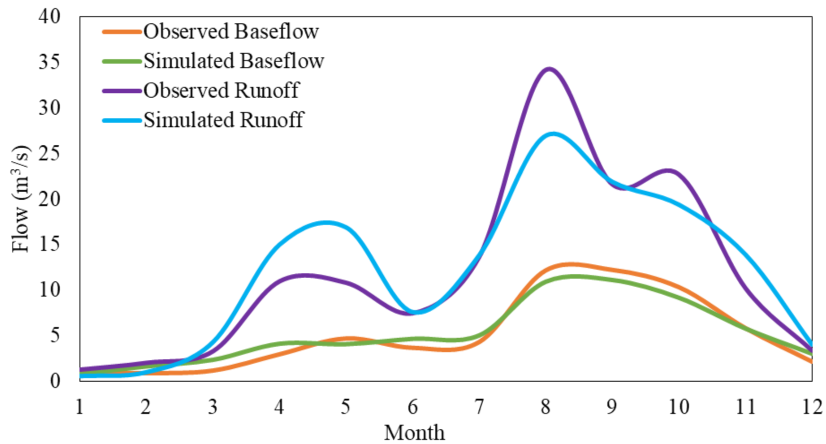

Figure 7. WetSpass-M model performance assessment.

3.3. Mean monthly surface runoff variability

Average monthly surface runoff had been estimated from 1986 to 2100 during baseline, short-term, and long-term periods for both RCP4.5 and RCP8.5 scenarios. The watershed's overall mean monthly estimate was 50.68mm during baseline period, whereas it has been rising by 3.68mm, 5.39mm, 2.16mm, and 9.77mm for the MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively (Fig. 8). The study areas' peak surface runoff was recorded in April by 98.31mm and 99.51mm for MidT4.5 and MidT8.5, while LongT4.5 and LongT8.5 in March by 100.99mm and 108.25mm, respectively. The lowest mean monthly surface runoff will be in December by 11.34mm, 11.03mm, 11.72mm, and 10.69mm for the MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively. In comparion to historical period, the overall monthly average percentage increase will be 8.70%, 18.22%, 6.53%, and 36.09% per month for MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively (Fig. 9). Furthermore, the watershed's highest monthly percentage increase in surface runoff will occur in March, at 67.09%, 127.86%, and 77.02% for MidT4.5, LongT4.5, and MidT8.5, respectively, while the LongT8.5 (268.78%) happening in February. Likewise, in comparison to the baseline period, the most notable per-month percentage decrease in surface runoff will occur in November, with figures of 38.28, 55.57, 45.09, and 36.69% for MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively.

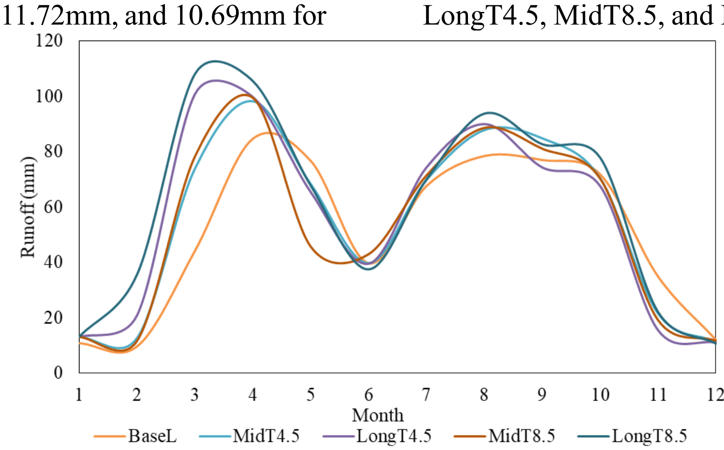

Figure 8. Projected mean monthly surface runoff.

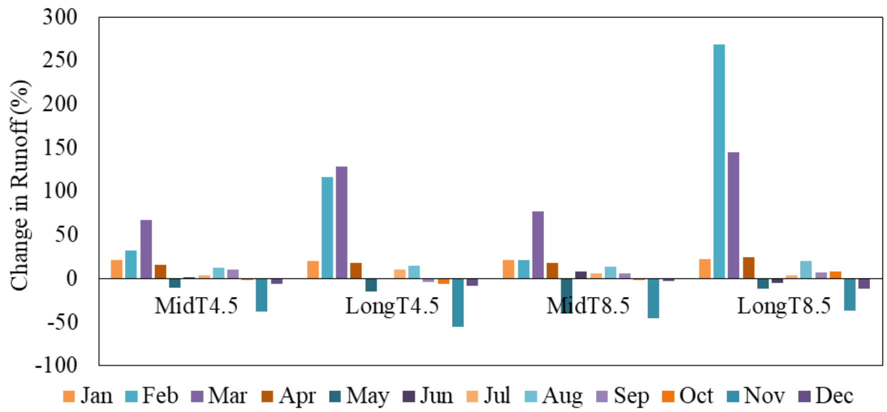

Figure 9. Percentage change of mean monthly surface runoff.

3.4. Seasonal surface runoff variability

The mean seasonal surface runoff for baseline period was 5.87mm, 78.16mm, 65.29mm, and 71.95mm, it increased by 6.83mm, 24.84mm, and 3.71mm for MidT4.5; 9.13mm, 81.84mm, and 5.71mm for LongT4.5; 5.63mm, 14.84mm, and 4.71mm for MidT8.5; and 16.13mm, 111.84mm, and 11.71mm for LongT8.5, corresponds to winter, spring, and summer, respectively (Fig. 10). However, the mean surface runoff during the autumn season was decreased by 16.95mm, 27.95mm, 20.95mm, and 30.95mm for MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively (Fig. 10). The mean seasonal percentage change of surface runoff has gone up for MidT4.5 (116.39%, 31.78%, and 5.68%), LongT4.5 (155.58%, 104.71%, and 8.75%), MidT8.5 (95.94%, 18.99%, and 7.21%), and LongT8.5 by 274.85%, 143.09%, and 17.94% for the winter, spring, and summer seasons, respectively (Fig. 11). On the other hand, the mean autumn seasonal percentage change of surface runoff has declined by 23.56%, 38.85%, 29.12%, and 43.02% for MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively (Fig. 11). In comparion to historical period, the seasonal surface runoff will be projected to increase throughout all seasons owing to climate change, except for autumn (Fig. 12).

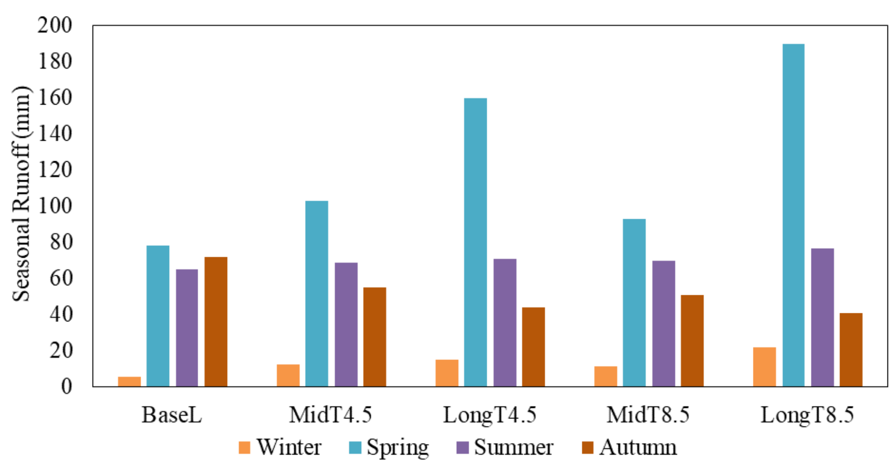

Figure 10. Projected seasonal surface runoff.

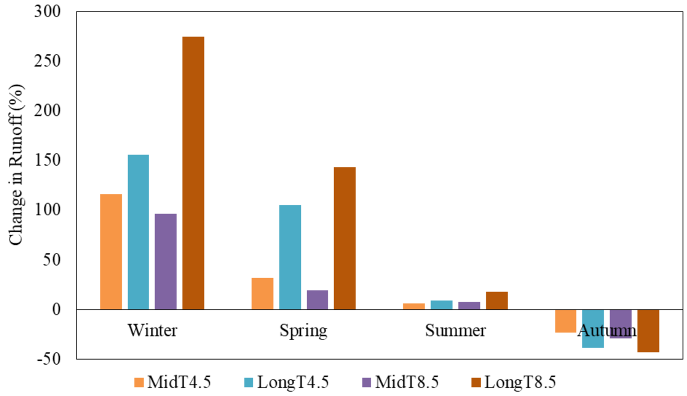

Figure 11. Projected seasonal change in mean surface runoff.

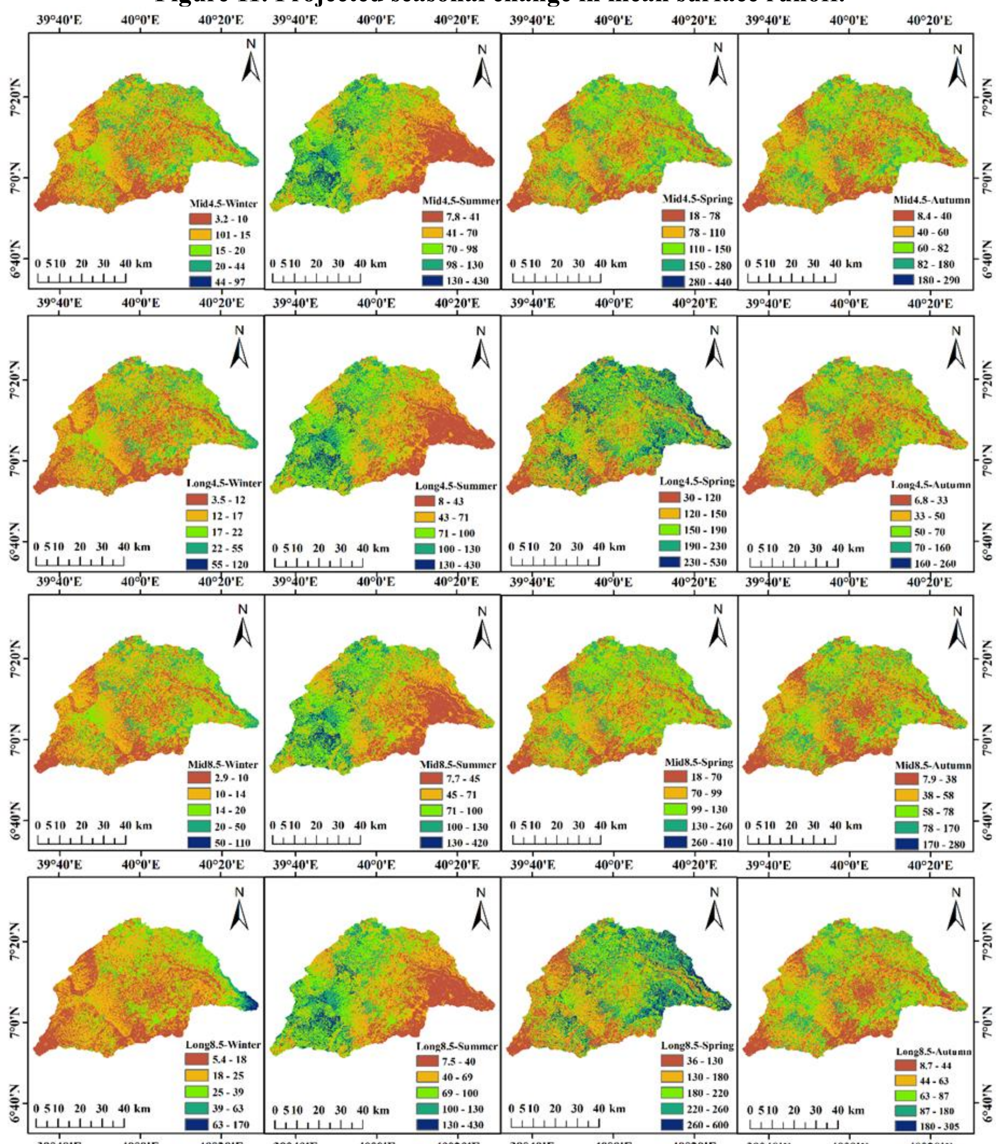

Figure 12. Seasonal spatio-temporal surface runoff variability. Note: Mid4.5: Mid-term for RCP4.5, Long4.5: Long-term for RCP4.5, Mid8.5: Mid-term for RCP8.5, and Long8.5: Long-term for RCP8.5 for winter, summer, spring, and autumn, respectively

3.5. Estimated annual surface runoff

In the Weyib watershed, the climate change implications are likely to increase annual surface runoff relative to the baseline period (Figs. 13 and 14). For instance, the mean annual surface runoff was 221.42mm, 239.69mm, 290.42mm, 225.32mm, and 330.48mm during the baseline period, MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively. Specifically, compared to the historical period, the average annual runoff will go up with amount of 18.27mm (8.3%), 68.99mm (31.2%), 3.89mm (1.8%), and 109.06mm (49.3%) for the MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively. Additionally, the baseline period's annual surface runoff peaked at 1070 mm; it will likely increase by 183mm (17.1%), 248mm (23.2%), 139mm (13.0%), and 320mm (29.9%) during the MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively. In the Weyib watershed, compared to the historical period (55mm), the lowest amount of annual runoff will increase by 1.8%, 32.7%, and 49.1% for MidT4.5, LongT4.5, and LongT8.5, respectively, while MidT8.5 declines by 7.3%. Similarly, Ethiopia's Disaster Risk Management Commission reported flood-affected areas in Oromia's Bale Zone and Somali's Afder Zone, which are located within and downstream of the Weyib watershed, respectively (NDRMC, 2020). Furthermore, frequent road inundation and traffic blockages occur due to significant surface runoff in the Shaya catchment (Aredo et al., 2021a).

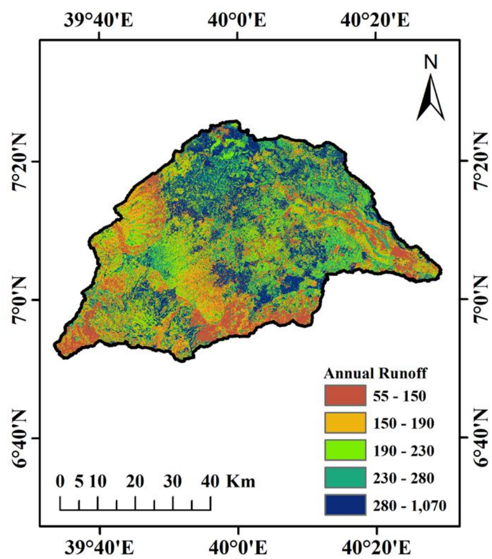

Figure 13. Mean annual runoff during the baseline period.

Only a few studies have examined the spatiotemporal variability of surface runoff over monthly, seasonal, and annual time scales (Asrade, 2024; Tadesse & Jothimani, 2024). In Ethiopia's numerous areas, the surface runoff and stream flow have varied dramatically compared to the baseline period (Ayele et al., 2016; Fita & Abate, 2022). For instance, in areas with declining future rainfall projections, a surface runoff estimation resulted in diminishing patterns (Shiferaw et al., 2018; Daba & You, 2020). Furthermore, the streamflow amount declined considerably compared to the baseline period in the Rift Valley basin's Gelana watershed (Daniel & Abate, 2022). The surface runoff increased in wet seasons in the Gilgel Abbay watershed (Ayele et al., 2016). Unlike Gilgel Abay, in the Gumara watershed, surface runoff will be projected to increase in both wet and dry seasons (Ayele et al., 2016). Similar to the Weyib watershed, the study area is experiencing a dramatic rise in surface runoff owing to projected increasing rainfall (Shiferaw et al., 2018; Fita & Abate, 2022). The surface runoff in the Awash and Nile basins will be expected to increase by thirty-four percent with rising annual rainfall (Gebrechorkos et al., 2020; Mengistu et al., 2021).

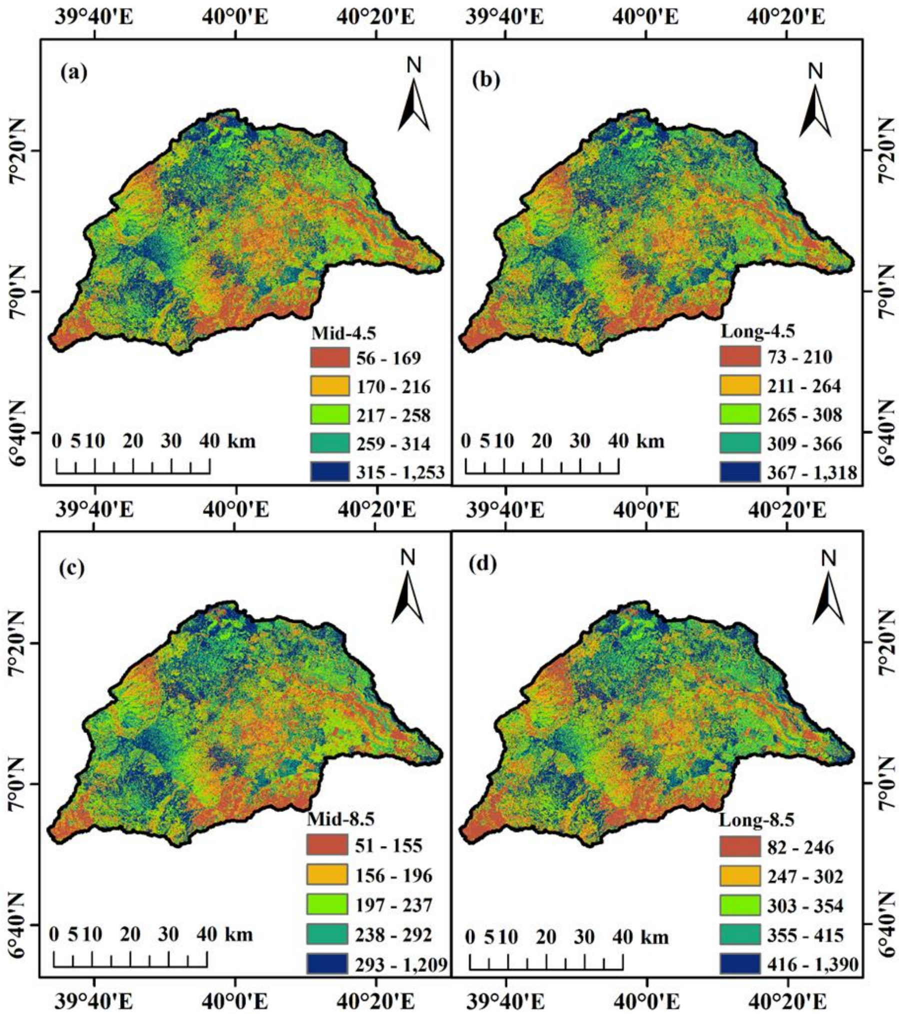

Figure 14 Spatial distribution of mean annual surface runoff: (a) Mid-term for RCP4.5, (b) Long-term for RCP4.5, (c) Mid-term for RCP8.5, and (d) Long-term for RCP8.5

In the Weyib watershed, the surface runoff had been rising noticeably with increasing mean temperature and rainfall (Figs. 8 to 14). Annual runoff had been increasing significantly, except for January, November, and December, based on three climate models in the watershed (Serur & Sarma, 2018). A considerable rainfall runoff process variability was recorded in the Shaya catchment (Aredo et al., 2021a; Aredo et al., 2021b). In the historical period, enormous amounts of surface runoff have been recorded in the watershed areas covered by settlement, agriculture, and bareland (Aredo et al., 2024a). Several road flooding incidents and congestion were observed in the study area due to LULC changes (Aredo et al., 2021a). In the Genale-Dawa basin's Yadot watershed, the streamflow has risen during the wet season due to increasing rainfall (Abdule et al., 2024). Similarly, Ethiopia's Disaster Risk Management Commission had reported flood-affected areas within and downstream of the Weyib watershed (NDRMC, 2020). On the other hand, this hydrological process variability undermines agricultural productivity and disrupts human life in the study area (Serur & Sarma, 2018; Tessema et al., 2020; Abebe et al., 2024). Furthermore, this basin faces considerable variability in the groundwater table (Kassahun & Mohamed, 2018). Even though some areas face a significant excessive amount of surface runoff and flooding, while the downstream areas were prone to drought due to climate change and variability (Awulachew et al., 2007; Mengistu et al., 2022;

Abebe et al., 2024). Additionally, the study area's water withdrawal from surface and groundwater sources has increased substantially (Aredo et al., 2023a; Aredo et al., 2023b).
Compared to the baseline period, a considerable amount of surface runoff will be recorded in the middle and downstream parts of the watershed. In the Weyib watershed, the research outcome underscored a need for medium-level priority to tackle and mitigate deteriorating watershed health indicators (Aredo et al., 2024b). This study noticed that vegetation-covered areas were less vulnerable to excessive surface runoff (Aredo et al., 2024a). Likely, a study confirmed that farmers residing in the study area are willing to make a greater difference toward improving ecological services while reducing harmful human activities (Kefale et al., 2021). Furthermore, joining hands to boost afforestation and water conservation activities to mitigate the effects of rising surface runoff due to climate change and other factors was imperative for the day-to-day life of human beings. Specifically, these require robust initiatives for afforestation, and mitigation efforts must be conducted to mitigate the effects of excessive surface runoff in vulnerable areas in the Weyib watershed and downstream areas. This study was conducted based on static groundwater levels in fifty-three boreholes throughout the primary wet season (late July to August) and the dry season (late November to December) in 2022. To address this data limitation in the study area, future studies can explore this further by collecting primary groundwater level data for a long-term period, covering a wide range of spatiotemporal scales.

4. Conclusions

This study aims to evaluate the surface runoff responses to climate change on a spatiotemporal level in the Weyib watershed, Ethiopia. This study ensembled five climate models and verified the WetSpass-M model to estimate spatio-temporal surface runoff under RCP4.5 and RCP8.5 scenarios spanning baseline, mid-term, and long-term periods. Statistical indices assessed model efficiency and performed well in the study areas. The findings of this study depict that the overall mean monthly surface runoff has been increasing by 3.68mm, 5.39mm, 2.16mm, and 9.77mm for the MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively. Furthermore, except for autumn, the surface runoff had increased on a seasonal scale. Precisely, the decline for the autumn season will be with 16.95mm, 27.95mm, 20.95mm, and 30.95mm for MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively. Compared to the baseline period surface runoff (221.42mm/year), the amount increased by 18.27mm, 68.99mm, 3.89mm, and 109.06mm for the MidT4.5, LongT4.5, MidT8.5, and LongT8.5, respectively. Concurrently with surface runoff, average temperature and rainfall will be projected to increase in the watershed. The outcomes of this study explicitly showed that climate change has been a driving factor in the rise of surface runoff, with the amount and effects rising continuously from the upstream areas to the downstream watershed's outlet. Furthermore, this increasing surface runoff will inundate the watershed's downstream areas, undermining agricultural activities and disrupting daily life. Moreover, stepping up reforestation, water conservation, and groundwater recharge initiatives is imperative to mitigate and lessen the effects of climate change-induced surface runoff in central and downstream high surface affected areas in the Weyib Watershed and the broader Ethiopia.

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Mesfin Reta Aredo: Conceptualization, methodology, formal analysis and investigation, visualization, resources, writing-original draft preparation.
Megersa Olumana Dinka: Supervised, reviewed, and edited the manuscript.

Conflicts of interest

The authors of this article declared no conflict of interest regarding the authorship or publication of this article.

Data availability statement:

All data generated or analyzed during this study are included in this published article.

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