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Quantifying the climate change impacts on the magnitude and timing of hydrological extremes in the Baro River Basin, Ethiopia

Shimelash Molla Kassaye[1*], Tsegaye Tadesse[2], Getachew Tegegne[3] and Aster Tesfaye Hordofa[4]

Abstract

Extreme hydrological events, like floods and droughts, exert considerable effects on both human and natural systems. The frequency, intensity, and duration of these events are expected to change due to climate change, posing challenges for water resource management and adaptation. In this study, the Soil and Water Assessment Tool plus (SWAT+) model was calibrated and validated to simulate flow under future shared socioeconomic pathway (SSP2-4.5 and SSP5-8.5) scenarios in the Baro River Basin with R2 values of 0.88 and 0.83, NSE of 0.83 and 0.74, and PBIAS of 0.39 and 8.87 during calibration and validation. Six bias-corrected CMIP6 Global Climate Models (GCM) were selected and utilized to investigate the effects of climate change on the magnitude and timing of hydrological extremes. All climate model simulation results suggest a general increase in streamflow magnitude for both emission scenarios (SSP2-4.5 and SSP5-8.5). The multi-model ensemble projections show yearly flow increases of 4.8% and 12.4% during the mid-term (MT) (2041–2070) and long-term (LT) (2071–2100) periods under SSP2-4.5, and 15.7% and 35.6% under SSP5-8.5, respectively. Additionally, the analysis revealed significant shifts in the projected annual 1 day, 3 day, 7 day, and 30 day maximum flows, whereas the annual 3 day and 7 day minimum flow fluctuations do not present a distinct trend in the future scenario compared to the baseline (1985–2014). The study also evaluated the timing of hydrological extremes, focusing on low and peak flow events, utilizing the annual 7 day maximum and minimum flow for this analysis. An earlier occurrence was noted for both peak and low flow in the SSP2-4.5 scenario, while a later occurrence was observed in the SSP5-8.5 scenario compared to the baseline. In conclusion, this study showed the significant effect of climate change on river hydrology and extreme flow events, highlighting their importance for informed water management and sustainable planning.

Keywords Timing of high flow and low flow, Climate change, CMIP6, SWAT+, Baro River Basin

Introduction

Water resources management and sustainable development depend on understanding river hydrology and its potential changes under future climate conditions (Shrestha et al. 2021). Changes in climate, specifically alterations in temperature and precipitation patterns, have the potential to significantly influence water availability, exacerbating both flooding and droughts (Majone et al. 2022). For example, the rainfall pattern may shift, causing more frequent and intense floods or prolonged droughts, thereby affecting availability and distribution (Murthy 2012; Society 2021). Moreover, climate change

*Correspondence:
Shimelash Molla Kassaye
shimemolla178@yahoo.com
[1] Hydrology and Water Resources Management, Africa Center of Excellence for Water Management, Addis Ababa University, Addis Ababa, P.O. Box 1176, Ethiopia
[2] National Drought Mitigation Center, School of Natural Resources, University of Nebraska-Lincoln, 815 Hardin Hall, 3310 Holdrege St., Lincoln, NE 68583-0749, USA
[3] Department of Civil Engineering, Addis Ababa Science and Technology University, Addis Ababa, P.O. Box 16417, Ethiopia
[4] Faculty of Water Resources and Irrigation Engineering, Arab Minch Water Technology Institute, Arba Minch University, Arba Minch, Ethiopia

can also alter the timing of hydrological extremes within the year, not only their magnitude (Lane and Kay 2021).

In addressing the challenge of climate change, a critical goal involves uncovering how climate change affects the mechanisms of the hydrologic cycle and forecasting its impact on related areas (Wang et al. 2016). Several researchers have explored the linkage between climate change and hydrological extremes (Taye et al. 2015; Lane and Kay 2021; Ich et al. 2022), with the majority reporting that extreme values are highly susceptible to climate change (Romanowicz et al. 2016; Bian et al. 2021; Ich et al. 2022; Tefera and Ray 2023). In general, as global temperatures rise, precipitation patterns become more erratic, directly affecting the flow's magnitude and increasing the risk of flash floods in some regions and intensifying drought conditions in others.

Environmental water requirements are influenced not only by the amount of water but also by its timing (Patil et al. 2023). A shift in the timing of streamflow will have substantial consequences for ecosystems, water availability, agricultural practices, and overall water resource management (Nachtergaele et al. 2016). For instance, even a slight change in the timing of floods can have a significant impact on the environment, increasing the risk of flooding, decreasing farm productivity (Klaus et al. 2016), and affecting the dependability of the water supply (Barnett et al. 2005). Some researchers have investigated the link between climate change and the timing of extreme flow events (Lane and Kay 2021; Society 2021; Fang et al. 2022; Patil et al. 2023). The consensus among them is that climate change does indeed cause shifts in the timing of hydrological extremes. However, these shifts can either be towards earlier or later dates, depending on regional and local factors. For example, statistically significant shifts with no consistent spatial pattern have been observed in China (Gu et al. 2017). Meanwhile, flood peaks in Scandinavia have shifted earlier in the year (Matti et al. 2017), whereas flood timing in Australia has shifted earlier in the year in tropical regions and later in the year in temperate areas, aligning with changes in antecedent moisture conditions (Wasko et al. 2020). Consequently, the timing of hydrological extremes needs to be assessed on a regional basis, taking into account the potential influence of spatial variations in climate changes and the unique physical attributes of each area.

In Ethiopia, there has been a lack of comprehensive research on hydrologic extremes, with no study conducted in the Baro River Basin (BRB). Although the common issue of flooding affecting the lower Baro downstream of Gambella is acknowledged, there have been no studies done to adequately quantify the extent of these extremes within the basin. Moreover, local communities have observed a shift in the timing of flooding from August to September, necessitating scientific validation from the past, extending through the present, and projecting into the future. Therefore, it is important to adequately quantify the magnitude and timing of these extremes using hydrological modeling. This will assist policymakers and stakeholders in developing appropriate strategies to mitigate adverse effects and adapt to the changing conditions.

Hydrological models can be used to investigate changes in both the magnitude and timing of peak and low flows and how these changes might occur with future climate conditions (Kay and Crooks 2014; Kiprotich et al. 2021; Pulighe et al. 2021). In this study, the soil and water assessment tool plus (SWAT+) model was employed to simulate flow in the Baro River Basin. The climate change impact analysis is based on the Global Climate Models (GCMs) output from the Coupled Model Intercomparison Project Phase 6 (CMIP6), considering both emission scenarios of Shared Socioeconomic Pathways (SSPs) SSP2-4.5 and SSP5-8.5, for the mid-term (2041–2070) and long-term (2071–2100) periods. The SSP2-4.5 scenario represents middle-of- the- road development where socio-economic factors follow their historical trends with no significant change, whereas SSP5-8.5 represents the worst-case scenario with the high end of the range of future pathways. These two scenarios were selected as they offer contrasting pathways that are relevant for studying potential impacts and policy implications across a range of sectors. The preference for the CMIP6 model arises from its higher resolution, expanded parameterization, and incorporation of updated emission scenarios, in contrast to the CMIP5 model. Additionally, the significance of the new SSP scenarios lies in their consideration of important socio-economic factors like population when making predictions (Siabi et al. 2023). Accordingly, the main goals of this study are to address the following questions: (i) What is the potential impact of climate change on the magnitude of low and high flows in the Baro River Basin? (ii) Is there a significant shift in the timing of the basin's extreme flows?

Materials and methods

Study area

The research was conducted in the Baro River Basin (BRB), located in southwestern Ethiopia and bounded by latitudes ranging from 7° 24 to 9° 25′ and longitudes from 33° 20′ to 36° 20′ (Kassaye et al. 2022), with its outlet in Gambella (Fig. 1). The basin is divided into upper and lower Baro regions at Gambella, covering an area of approximately 23,400 km^2 with an altitudinal range of 400 and 3500 m. Notably, 42% of the areas lies between 1000m and 2000 m in altitude (Getu Engida et al. 2021). The lower Baro is a floodplain area dominated by

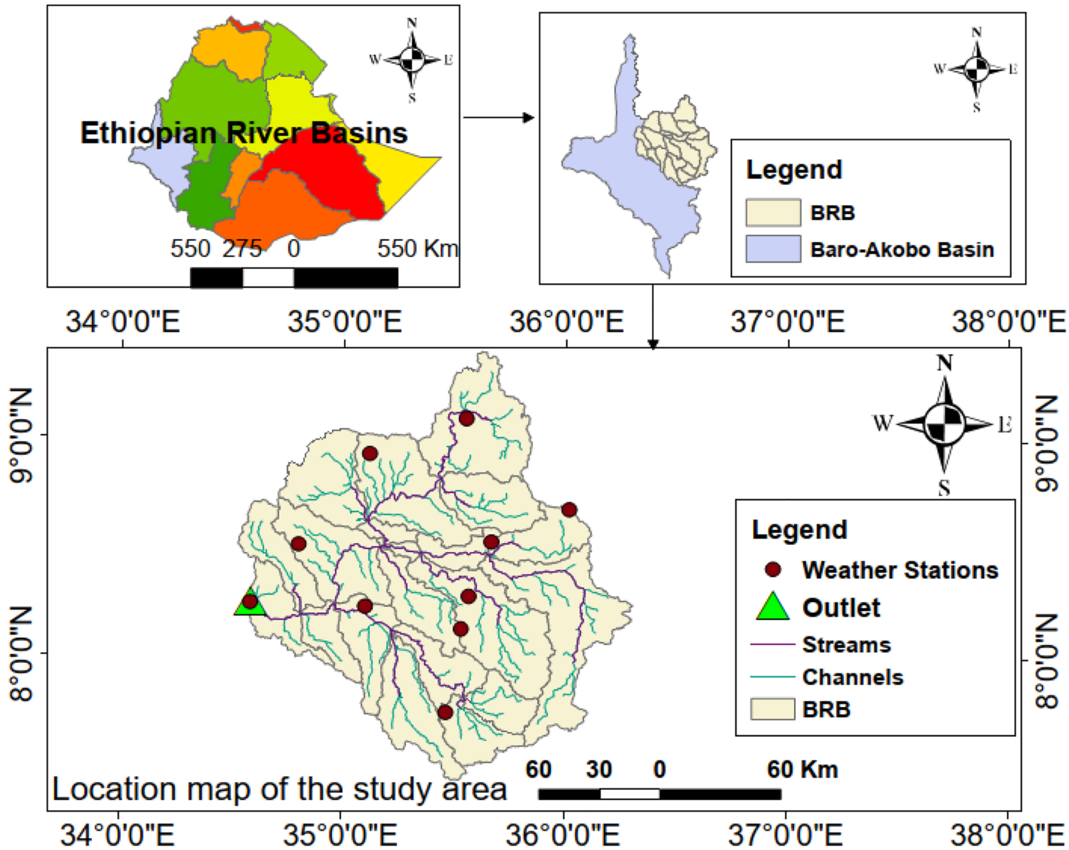

Fig. 1 Location map of the study area

grassland and woodland (Moges and Taye 2019), whereas the upper Baro is mostly covered by agriculture and forest.

The entire basin is characterized by a single monsoon wet season that typically occurs from late May or early June to the end of September, experiencing annual precipitation ranging from 1100 mm to 2500 mm. Moreover, the basin experiences temperature extremes ranging from 17.7 to 42 °C for maximum temperatures and 6.4 to 27 °C for minimum temperatures (Kebede 2013; Kassaye et al. 2022). Subsequently, this wet season is followed by a long dry season.

From the geological perspective, the BRB follows a distinctive pattern (Alemayehu et al. 2016; Bayou et al. 2021). It begins with the presence of Precambrian crystalline basement rocks forming the foundational layer. Overlying these are sediments dating from the late Paleozoic to the early Tertiary period. Subsequently, these sediments are covered by Cenozoic volcanic rocks along with associated sedimentary formations. While the precise coverage and depth of each rock type remain unknown, all three major categories: the ancient Precambrian basement rocks, the Tertiary to Quaternary volcanic rocks, and the substantial Neogene sedimentary deposits exist within the region, albeit varying in depths and lateral extent. This geological sequence signifies a complex layering of rock formations that have evolved over extensive periods, contributing to the diverse geological landscape of the upper Baro River Basin.

The Upper Baro River Basin in Ethiopia exhibits a diverse range of dominant soil types, each playing a pivotal role in shaping the region's agricultural landscape. Vertisols, Nitisols, Cambisols, and Fluvisols are among the dominant soil types encountered across the basin (Alemayehu et al. 2018), each exhibiting specific characteristics influenced by factors such as topography, climate, and geological formations.

Data quality analysis

Hydro-meteorological datasets

Observed streamflow data for BRB at Baro Gambella were collected from Ethiopia's Ministry of Water and Energy for the period from 1980 to 2021. Similarly, meteorological data, including precipitation, maximum and minimum temperature, wind speed, humidity, and sunshine hour data, were collected from the Ethiopian

National Meteorological Agency (ENMA) for the period from 1990 to 2021. A 30 year base period was selected for this analysis, starting from 1985 to 2014, based on the availability of climate data.

In the initial phase of this study, we conducted data quality control procedures. This involved assessing data availability, identifying and addressing outliers, conducting a homogeneity test, and subsequently filling in any missing data, following the guidelines provided by (Kassaye et al. 2022) for the BRB. After checking the outlier test and homogeneity test, the missing values were filled using the inverse distance weighted (IDW) method, where six stations were selected based on the quality of data, as shown in Table 2.

Geospatial datasets

In addition to the meteorological data, SWAT+ also utilizes spatial data such as the Digital Elevation Model (DEM), Soil, and land use/land cover data (LULC) as input for simulating flow. The DEM, with a 30 m resolution, was derived from the Shuttle Radar Topography Mission (SRTM), and it was employed for delineating the basin (Fig. 2).

Land use/cover (LULC) data were obtained from the Ethiopian Geospatial Agency for the year 2016. Within the basin, the LULC classes were classified into four primary classes based on their dominant features: AGRL (Agricultural land-generic), RNGE (Schrubland), FRST (Forest-mixed), and AGRC (Agricultural land close grown). Furthermore, spatial soil data were collected from the Ethiopian Ministry of Water and Energy, and the soil types were reclassified into nine classes based on their dominance.

Methods

Climate model data

The Copernicus Climate Change Service was utilized to extract data from the CMIP6 climate data archive. In total, six climate models were identified for the study area based on the availability of all variables (rainfall, Tmax, and Tmin) for both historical and future periods. To refine the selection, the models were filtered based on daily data, a nominal resolution of 100 km, a source type of Atmosphere-Ocean General Circulation Model (AOGCM) with the r1p1f1 variant, as recommended by (Balcha et al. 2022) (Table 1).

This study investigated the impact of climate change on the magnitude and timing of selected hydrological extremes during the mid-term (2041–2070) and long-term (2071–2100) periods compared to the historical

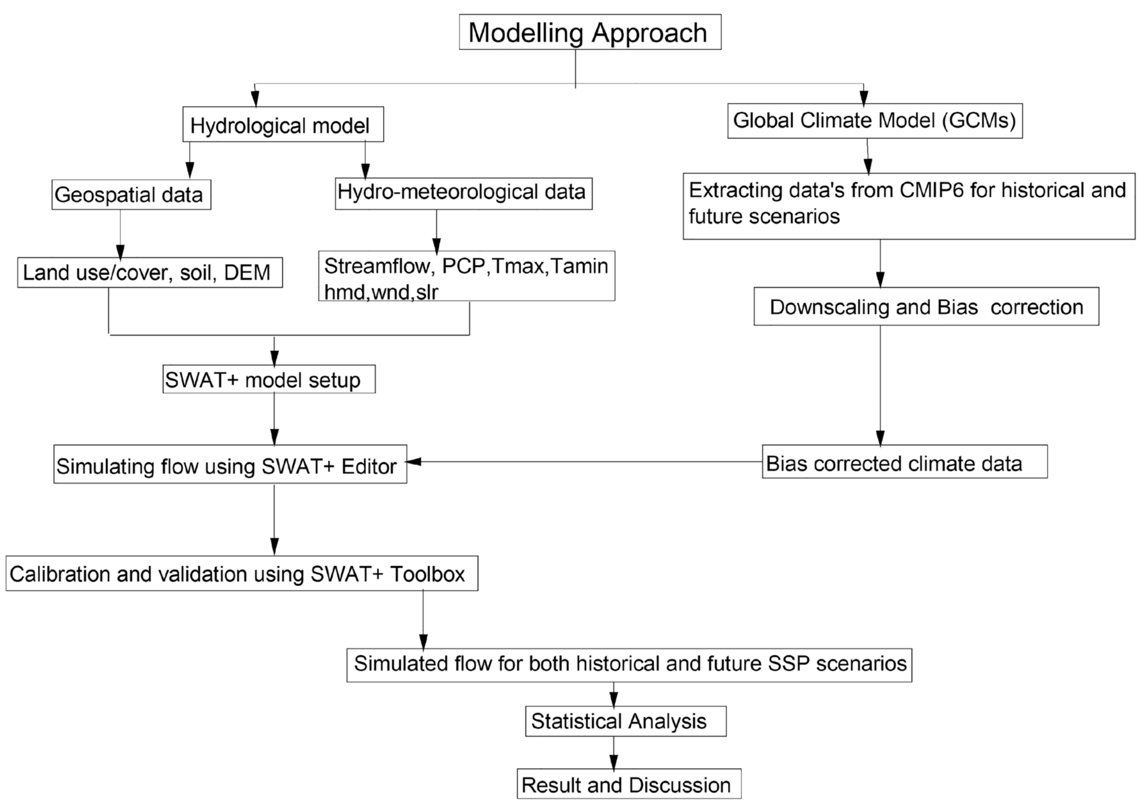

Fig. 2 Flowchart showing the general methodology used in the study

Table 1 List of CMIP6 climate models selected for climate projection in BRB

No	CMIP6 Model Name	Country	Resolution (lon. Lat. deg)
1	EC-Earth3-CC	Europe	0.7°× 0.7°
2	EC-Earth3-Veg	Europe	0.7°× 0.7°
3	INM-CM4-8	Russia	2°× 1.5°
4	INM-CM5-0	Russia	2°× 1.5°
5	MRI-ESM2-0	Japan	1.1°× 1.1°
6	NorESM2-MM	Norway	0.9°× 1.3°

Table 2 Meteorological stations used in the SWAT + model

Stations	Lat (deg)	Long (deg)	Data period
Masha	7.75	35.4667	1980–2018
Gore	8.1333	35.5333	1980–2018
Itang	8.1667	34.2667	1980–2016
Gambella	8.25	34.58333	2000–2018
Metu	8.28333	35.56667	1981–2018
Dembidollo	8.516667	34.8	1987–2018

period (1985–2014). The models were divided into three 30 year intervals: 1985–2014 as the historical period, 2041–2070 as the mid-term period, and 2071–2100 as the long-term period.

In contrast to actual observations, climate outputs derived from GCMs consistently exhibit systematic biases (Mehrotra and Sharma 2015). Hence, it is essential to perform some form of statistical adjustment before utilizing them in any application. In this study, the Climate Model Data for Hydrological Modelling (CMhyd) tool was employed to downscale and bias-correct rainfall and temperature data using the distribution mapping method (Musie et al. 2020). This tool has found extensive usage in correcting biases in precipitation and temperature data for various applications (Tian et al. 2020). For instance, Zhang et al. (2018) found that among the five bias correction algorithms tested, the distribution/Quantile mapping emerged as the most effective in terms of performance.

Soil and water assessment tool plus (SWAT +) application

SWAT+ (Soil and Water Assessment Tool Plus) is an advanced hydrological modelling framework that extends the capabilities of the well-established Soil and Water Assessment Tool (SWAT) (Chawanda 2021). It integrates various components to comprehensively model watershed processes, including hydrology, water quality, land use, and climate interactions. One of the key features of SWAT+ is its ability to simulate complex hydrological processes at different spatial and temporal scales, making it a valuable tool for studying watersheds and their responses to changing environmental conditions (Akoko et al. 2021).

At its core, SWAT+ employs a process-based approach to simulate water movement, erosion, nutrient cycling, and pollutant transport within a watershed. It partitions the watershed into sub-basins and further divides them into hydrological response units (HRUs) based on land use, soil types, topography, and other relevant factors. This allows for a detailed representation of landscape heterogeneity and its impact on water flow, sediment transport, and nutrient dynamics. The model considers various hydrological components, such as precipitation, evapotranspiration, surface runoff, infiltration, groundwater flow, and streamflow routing, to simulate the movement and fate of water through the watershed. SWAT+ also incorporates climate data, enabling the assessment of climate change impacts on hydrology and water resources by integrating future climate projections into the simulations.

The SWAT+ model requires point inputs of precipitation (PCP), temperature (both Tmax and Tmin), wind speed (wnd), relative humidity (hmd), and sunshine hour's (slr) data for simulating river flows (see Table 2 below). In this study, three distinct sets of model simulations were conducted, each utilizing different input data: (1) using climate data over the baseline period of 1985–2014; (2) using climate data for the near-future period 2041–2070 for both SSP2-4.5 and SSP5-8.5 scenarios; and (3) using climate data for the long-term future period 2071–2100 for both SSP2-4.5 and SSP5-8.5 scenarios.

The area was divided into 19 sub-basins using DEM data, with 15.4% constituting floodplain and the remaining 84.6% of the landscape representing upslope terrain. Taking the short channel merging threshold as 5%, a total of 118 channels were generated during this delineation process. The basin is dominated by four classes of landuse as AGRL, RNGE, FRST, and AGRC. Additionally, the basin is classified into three slope classes: 0–15%, 15–30%, and >30%.

During the simulation period, observed climate data from five representative stations were used as an input, selected based on the completeness of their data (Table 2). The model setup involved utilizing the Soil Conservation Service's Curve Number (CN) method for runoff estimation, the Hargreaves method for actual evapotranspiration (ET) estimation, and the Muskingum method for flow routing.

Sensitivity analysis

The SWAT+ Toolbox, specifically designed to work with the SWAT+ model, was used for model sensitivity analysis, calibration, evaluation, and validation. The SOBOL sensitivity analysis method was employed to identify and screen the most sensitive parameters, examining which input parameter had the most impact on the model's output (Hordofa et al. 2023) before initiating the calibration process. The software automatically calculates sensitive parameters and ranks them in ascending order (Hordofa et al. 2023).

Model simulation, calibration, validation, and performance criteria

After identifying sensitive input parameters, calibration was conducted by adjusting the model parameters to align observed and simulated flows. Subsequently, using the identified input parameters, the model underwent validation using another set of data to ensure its reliability and suitability for real-world applications. The model underwent simulation for the 30 year baseline period spanning from 1985 to 2014.

The SWAT+ model's performance was evaluated using goodness-of-fit statistics, involving a comparison between the observed and simulated streamflow data. Various statistical metrics, such as the Nash-Sutcliffe (NSE), bias percentage (PBIAS), and coefficient of determination (R2), were employed for this assessment. These metrics served as indicators of how well the model's predictions aligned with the actual streamflow data, providing valuable insights into the model's accuracy and reliability.

Impact of climate change on the magnitude and timing of hydrological extremes

The influence of climate change on hydrological extremes is substantial, resulting in an increased frequency and heightened severity of diverse hydrological events. These changes are attributed to rising global temperatures, altered precipitation patterns, and other shifts in weather systems. The effect can be observed in the magnitude and timing of hydrological extremes.

Impact of climate change on the magnitude of hydrological extremes

The impact of climate change on the magnitude of hydrological extremes is significant and evident across various regions. A statistical approach was used for the analysis of low flow and high flow in the river. Within this research, high flows are represented by the maximum flows observed over annual 1 day, 3 day, 7 day, and 30 day periods, calculated using daily average discharge data. Conversely, low flows are indicated by the annual 7 day and 30 day minimum discharge values. Those indices are extracted from daily flow data using the Annual Maximum Series (AMn) Model (Gregor 2010) from the Hydro Office package.

Impact of climate change on timing of hydrological extremes

For determining the timing of hydrological extremes, the first step was identifying the day of the year when the annual maximum of 7 day and 30 day for peak flow analysis and the annual minimum7 day and 30 day for low flow occurs using AMn statistical tool from Hydro Office Package. The AMn software (Gregor 2010) allows calculating extreme (N-daily) values from time-series data. To analyze any potential shift in the timing of hydrological extremes under both the baseline and future scenarios (SSP2-4.5 and SSP5-8.5), the mean day of occurrence was estimated using a circular mean package from R programming. In general, the methodologies employed in this study are summarized in the figure below (Fig. 2).

Results and discussion

Calibration and validation of the SWAT + model

Six climate models from CMIP6 (MRI-ESM2-0, NorESM2-MM, EC-Earth3-Veg, EC-Earth3-CC, INM-CM5-0, and INM-CM4-8) were selected based on (i) the common availability of climatic variables (Tmax, Tmin, and PCP) for historical, mid-term (MT), and long-term (LT) periods, and (ii) availability for the two scenarios SSP2-4.5 and SSP5-8.5. The distribution mapping method from CMhyd was employed to downscale and bias-correct the climate data.

Observed data from 2002 to 2010 and 2012 to 2016 were then used to calibrate and validate the SWAT+ model, respectively. Subsequently, flow simulations were performed for future periods. The results showed very good agreement between the observed and simulated values (Fig. 3). The goodness of fit was assessed using NSE, PBIAS, and R2, with respective values of 0.83, 0.39, and 0.88 during calibration and 0.74, 8.87, and 0.83 during validation, respectively (Table 3).

Evaluation and projection of streamflow

The initial phase of the analysis involved a comparison between the observed and simulated streamflow time series spanning from 1985 to 2014. Fig. 4 below illustrates the results, revealing that for the winter (December, January, and February-DJF), summer (June, July, and August-JJA), and spring season (September, October, and November-SON), climate models INM-CM5-0 and INM-CM4-8 demonstrated better simulation results compared to other climate models. The average percentage change between observed and simulated

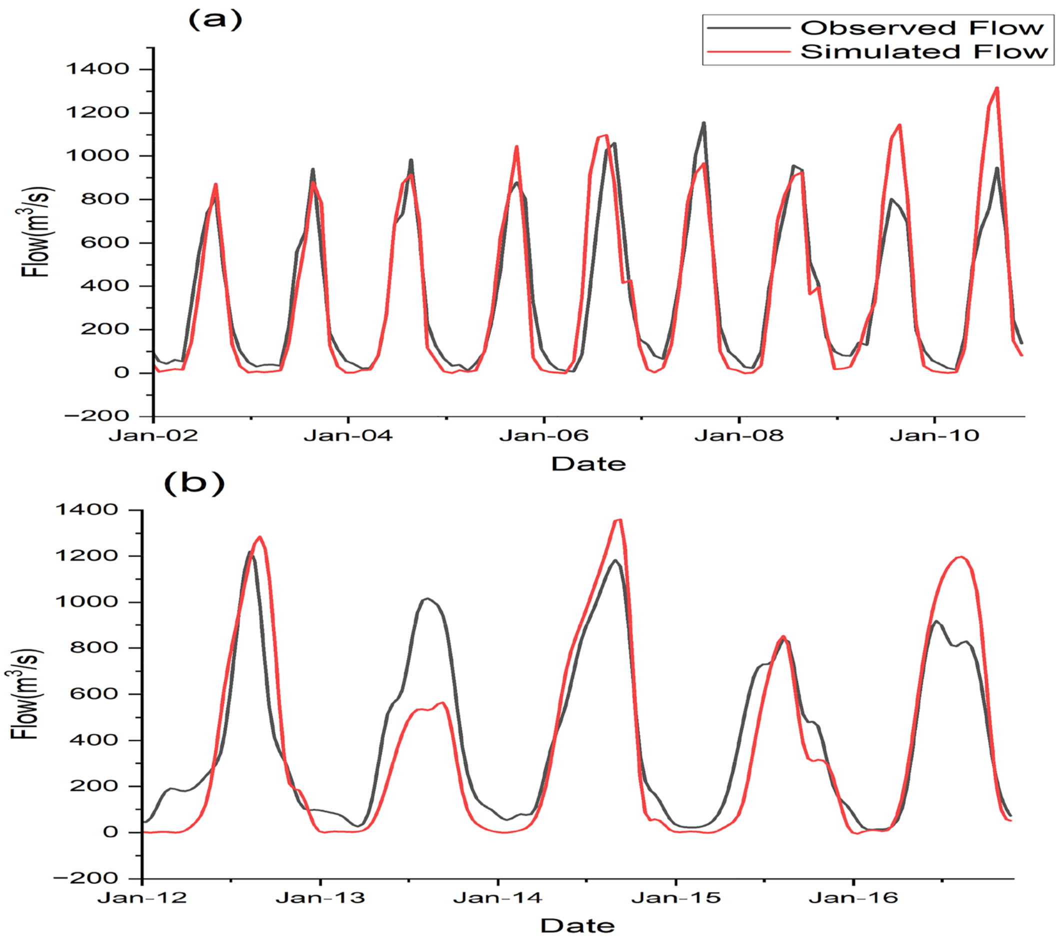

Fig. 3 Comparison of observed and simulated monthly streamflow for **a** the calibration period (2002–2010) and **b** the validation period (2012–2016)

Table 3 Results of the simulated evaluation of the streamflow during both calibration and validation periods in the Baro River using SWAT+

Evaluation criteria	Value during calibration	Value during validation
NSE	0.83	0.74
PBIAS	0.39	8.87
R2	0.88	0.83

flows for those seasons varies within the range of 5–10%. However, during the autumn season (March, April, and May-MAM), INM-CM5-0 and INM-CM4-8 underestimated the flow, while NorESM2-MM provided a better estimation with an average difference of 3% between the simulated and observed flows. Generally, climate models EC-Earth3-CC and MRI-ESM2-0 overestimated the flow (Fig. 4).

Numerous researchers worldwide have recognized the value of employing multi-model ensembles to enhance the quality of climate data, primarily in the context of model evaluation (Kattsov et al. 2013; Tegegne and Melesse 2020; Yimer et al. 2022). However, it's important to understand that the concept of ensembles doesn't mandate the inclusion of all available climate models; instead, the focus should be on selecting the most proficient models. This notion is supported by the findings of Yimer et al. (2022), indicating that the effectiveness of ensemble models doesn't necessarily depend on the quantity of individual models used in the ensemble creation process.

Weighted average ensemble climate models employ various methods to assign varying weights to individual model simulations within the ensemble. These methods are designed to enhance prediction accuracy by assigning greater importance to simulations considered more reliable, skilled, or credible. There are different types of weighted average ensembles, including expert-weighted

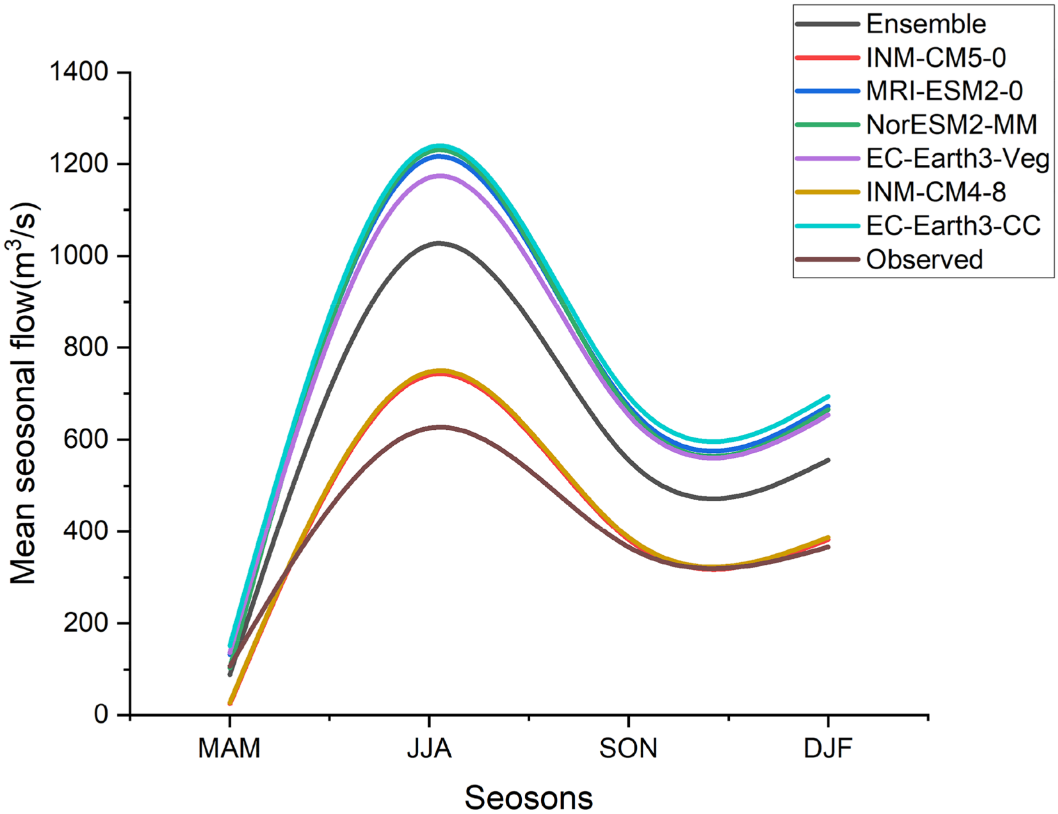

Fig. 4 Comparison of climate models with observed flow

ensembles, performance-based ensembles, model skill scores and ranking, machine learning-based weighting, and hybrid approaches. In our study, we utilized a hybrid approach that relies on expert judgment along with statistical methods to assign weights. Consequently, we compared the simulated climate data against the observed data, excluding those models that significantly overestimated or underestimated the flow. Subsequently, the mean of those better-performing climate models was taken and showed a good representation of flow. This finding was supported by the result of Mengistu et al. (2023), where they observed that the ensemble mean of the climate models exhibited a better correlation with observed values in the Baro River Basin (BRB). Researchers such as Gu et al. (2018; Chakilu et al. (2023); and, Terefe and Dibaba (2023) also used mean ensemble climate models to evaluate the impact of climate change on hydrological extremes, finding good performance with the observed data in their analysis. Based on our result, the mean multi-model ensemble value of four models (INM-CM5-0, INM-CM4-8, EC-Earth3-Veg, and NorESM2-MM) was used in the subsequent section for assessing the impact of climate change on hydrological extremes.

Projected changes in streamflow

The different projections from Global Climate Models (GCMs) were used as input for simulating streamflow using the SWAT+ model for various climate scenarios: baseline (1985–2014), SSP2-4.5 (2041–2070 and 2071–2100), and SSP5-8.5 (2041–2070 and 2071–2100). The streamflow series showed that almost all of the models exhibited similar trends to the observed series across all time steps. During the baseline period, the annual mean ensemble flow varied from 447.7 to 783.7m^3/s. In contrast, under SSP2-4.5, it ranged from 472.6 to 894.7 m^3/s, and under SSP5-8.5, it ranged from 511.8 to 1238.7 m^3/s (Fig. 5). Table 4 below shows the mean annual flow and the percentage change between the baseline period and the two future scenarios SSP2-4.5 and SSP5-8.5 for the ensemble climate models.

Impact of climate change on the magnitude of hydrological extremes

Climate change impact on the high flows

To comprehend future flow trends, we estimated the annual maximum flows for 1 day, 3 day, 7 day, and 30 day periods, as shown in Fig. 6. The analysis reveals that the 1-day maximum flow shows greater fluctuations,

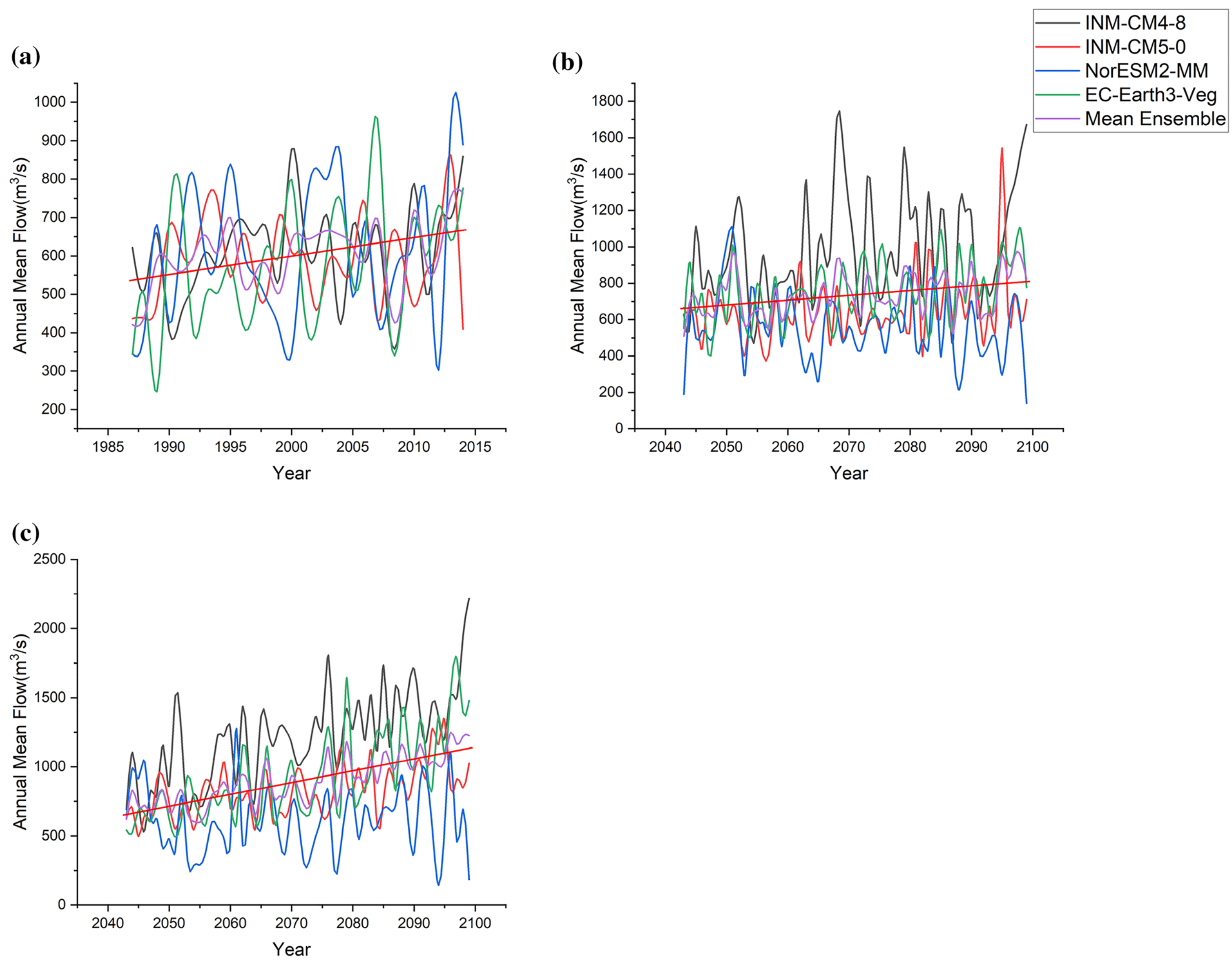

Fig. 5 Flow simulated for the three distinct periods **a** 1985–2014 (baseline), **b** 2041–2100 (SSP2-4.5), and **c** 2041–2100 (SSP5-8.5)

Table 4 Mean annual flow changes from mean ensemble models

Scenario	Baseline	SSP2-4.5	SSP5-8.5
Flow in Cumec	691.8	780.8	899.2
Percentage change relative to the baseline	–	12.8%	29.9%

indicating an average percentage shift of 49.8% under SSP2-4.5 and 80% under the SSP5-8.5 scenario compared to the baseline. These findings agree with the results found by Yang et al. (2022), which indicate greater variability in the 1 day maximum compared to other periods.

In contrast, the annual 3 day maximum flow shows relatively less variability, experiencing an average rise of 33% under SSP2-4.5 and 58.4% under SSP5-8.5 relative to the baseline. Similarly, the annual 7 day maximum flow exhibits less fluctuations, with a percentage alteration of 22.3% under SSP2-4.5 and 40.1% under SSP5-8.5 compared to the reference period. Remarkably, the annual 30 day maximum flow presents the least variability, depicting a percentage shift of − 5.1% under SSP2-4.5 and 28.7% under SSP5-8.5.

The 1 day maximum flow is more prone to greater fluctuations due to its sensitivity to short-term extreme events, such as intense rainfall, sudden storms, or rapid snowmelt. It reacts swiftly to immediate changes in precipitation or watershed conditions, resulting in increased fluctuations as it emphasizes the most extreme values within a very short timeframe. On the other hand, the longer timeframes of the 3 day, 7 day, and 30 day maximum flow tend to smooth out fluctuations, providing a more averaged and sustained view of the watershed's hydrological behavior over extended durations.

Additionally, the annual maximum series was extracted and plotted using the Flow duration curve (FDC) for all time periods. The results displayed significant variations

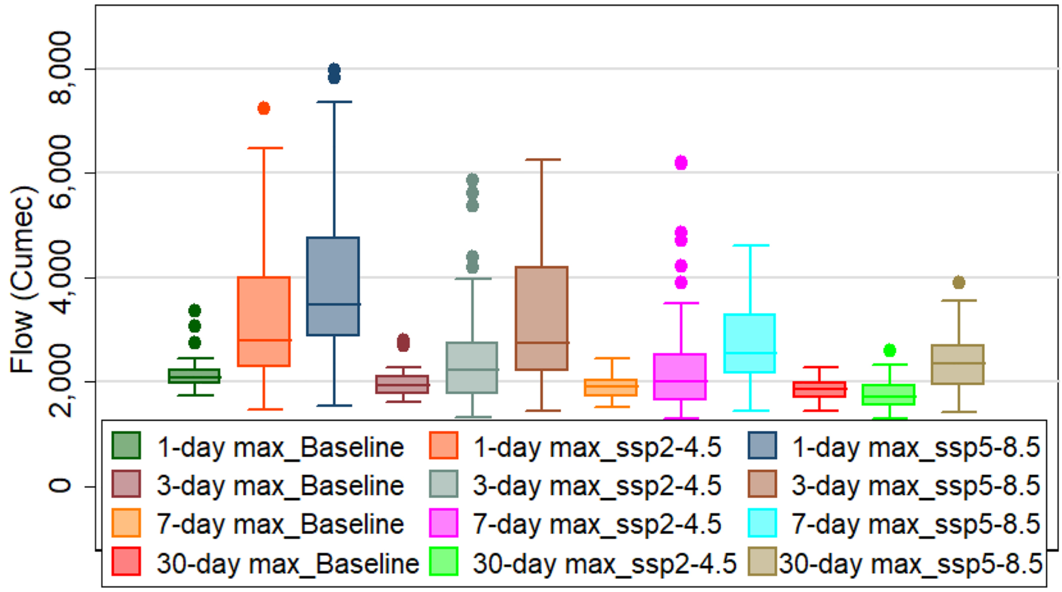

Fig. 6 1,3,7, and 30-day annual maximum flow trend for baseline, SSP2-4.5, and SSP5-8.5

across each period. To assess alterations in the basin's high flow pattern, magnitudes were classified into four groups based on their probability of exceedance (Q0-Q25, Q26-Q50, Q51-Q75, and Q76-Q100). Within this classification, the SSP5-8.5 scenario exhibited greater changes in high flow across all probabilities of exceedance (Fig. 7). Notably, the change in high flow is most noticeable in Q0-Q25, indicating higher magnitudes (Table 5).

Climate change impact on low flows

Just like floods, low-flow events are naturally occurring phenomena capable of significantly hindering various river applications and functions. These impacts extend to the environment, inland waterway navigation, hydropower generation, sediment control, and more (Ionita and Nagavciuc 2020). To assess the future hydrological drought conditions, we computed the annual 3 day and 7 day low flows for all scenarios, including the baseline,

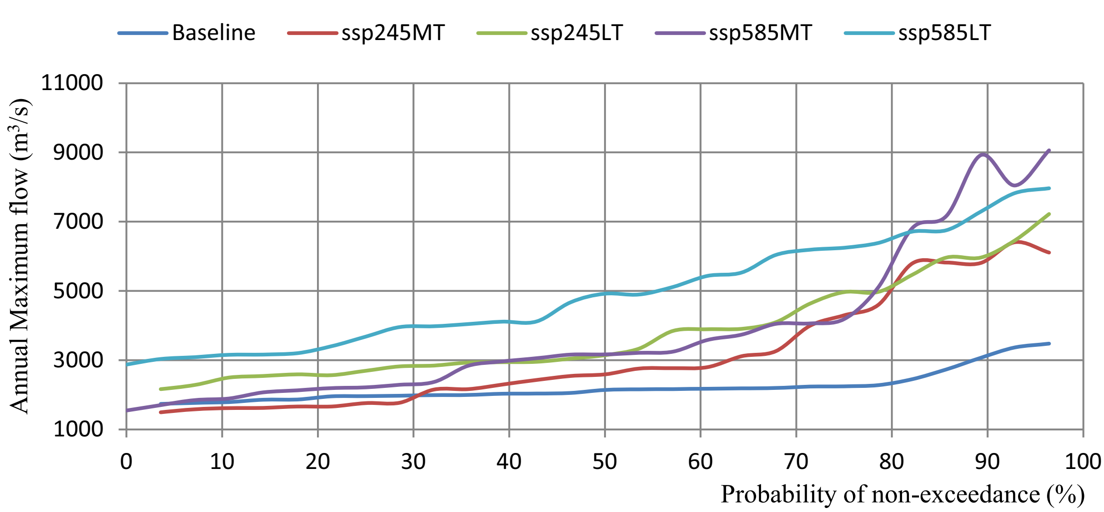

Fig. 7 Flow duration curve for high flows in the basin

Table 5 Mean annual maximum flow based on the range of probability of exceedance

Q0-Q25					Q26-Q50					Q51-Q75					Q76-Q100				
BF	SSP245		SSP585			SSP245		SSP585			SSP245		SSP585			SSP245		SSP585	
	MT	LT	MT	LT	BF	MT	LT	MT	LT	BF	MT	LT	MT	LT	BF	MT	LT	MT	LT
2806	5549	5861	7044	7028	2182	3042	3838	3581	5448	2008	2162	2892	2700	4082	1830	1609	2442	1974	3176

SSP2-4.5, and SSP5-8.5, as shown in the figure below (Fig. 8).

Contrary to the consistently rising trend observed in peak flow for all time periods and scenarios, the trend in low flow doesn't uniformly show an increase across all scenarios. However, when examining annual averages, the low flows demonstrate a slight increase in the future. According to (Terefe and Dibaba 2023), this might be due to a rise in precipitation magnitude in the basin under both the SSP2-4.5 and SSP5-8.5 scenarios.

The results from various researchers (Assefa and Moges 2018; Fangmann and Haberlandt 2019), as well as the findings in this paper, show that the magnitude of low flow might either increase or decrease in response to climate change. This is in contrast to peak flow, which generally experiences an increase in magnitude with the increase in global climate. This distinction arises because high flow is more responsive to climate change, while low flow is significantly influenced by changes in land use/cover, as highlighted by (Gedefaw et al. 2023).

Impact of climate change on the timing of hydrological extremes

Climate change impact on the timing of high flows

The timing of hydrological extremes refers to their occurrence concerning the water cycle, such as floods, droughts, and another water related phenomenon, at specific times or seasons. Changes in hydrological extremes can be influenced by factors like seasonal patterns, climate variability and change, geographic and topographic factors, El Nino and La Nina events, and human activities. Therefore, an understanding of hydrological extremes is crucial for effective water resources management and climate change adaptation.

In this study, the timing of peak flow was determined based on the annual 7 day maximum flow and annual 30 day maximum flow under climate change. Initially, the occurrence of these maximum flows was extracted from daily hydrological data using statistical tools. Then, peak flow average events were estimated using a circular mean package in R. The timing of occurrences was estimated for different periods, including historical, SSP2-4.5 for the MT (2041–2070, and LT (2071–2100) periods, as well as for SSP5-8.5 for the MT (2041–2070) and LT (2071–2100) periods. The number of days was calculated starting from January 1 to December 31 for 366 days.

Based on the 7 day annual maximum, the results showed that the date of occurrence of peak flow varies between days 238 and 261. It is projected to drop by 2 days under the mid-term SSP2-4.5 scenario (2041–2070) and 25 days under the long-term SSP2-4.5 scenario (2071–2100). On the other hand, under the SSP5-8.5 scenario, the date of occurrence of the 7 day annual maximum falls within the days of 265 and 273. It is projected to shift forward by 10 days and 2 days under SSP2-4.5(2041–2070) and (2071–2100), respectively (Table 6).

In contrast to the SSP2-4.5 scenario, there is a forward shift in the date of occurrence of the annual 7 day maximum under the SSP5-8.5 scenario. This result corresponds with the outcomes presented in (Dembélé et al. 2023), where they revealed that the annual maximum flow drops by 2 days under the future scenario of RCP2.6, RCP4.5, and RCP8.5 in their study in the Volta River Basin.

When comparing the effects of climate change on peak flow timing between the long-term (2071–2100) and mid-term (2041–2070) future scenarios, it was noted that the timing of long-term period moves towards earlier dates. This finding was supported by (Robles et al. 2017), who identified a connection between warmer temperatures and a shift towards earlier occurrence of spring flows.

Climate change impact on the timing of low flow

Similar to the peak flow analysis, the timing of low flow was also estimated both for the baseline period and future scenarios. This analysis was conducted based on the annual-7 day minimum flow and annual-30 day minimum flow, as presented in Table 7 below. The findings indicate that the timing of the annual 7-day minimum flow ranges from the 53rd to the 58th day, showing a drop in 4 days and 9 days under the SSP2-4.5 scenarios (2041–2070) and (2071–2100), respectively. In contrast, a forward shift in timing by 17 days and 5 days was observed for the annual-7 day minimum flow under the SSP5-8.5 scenarios (2041–2070) and (2071–2100), respectively. Moreover, it was noticed that the timing of the monthly minimum flow occurs around March for

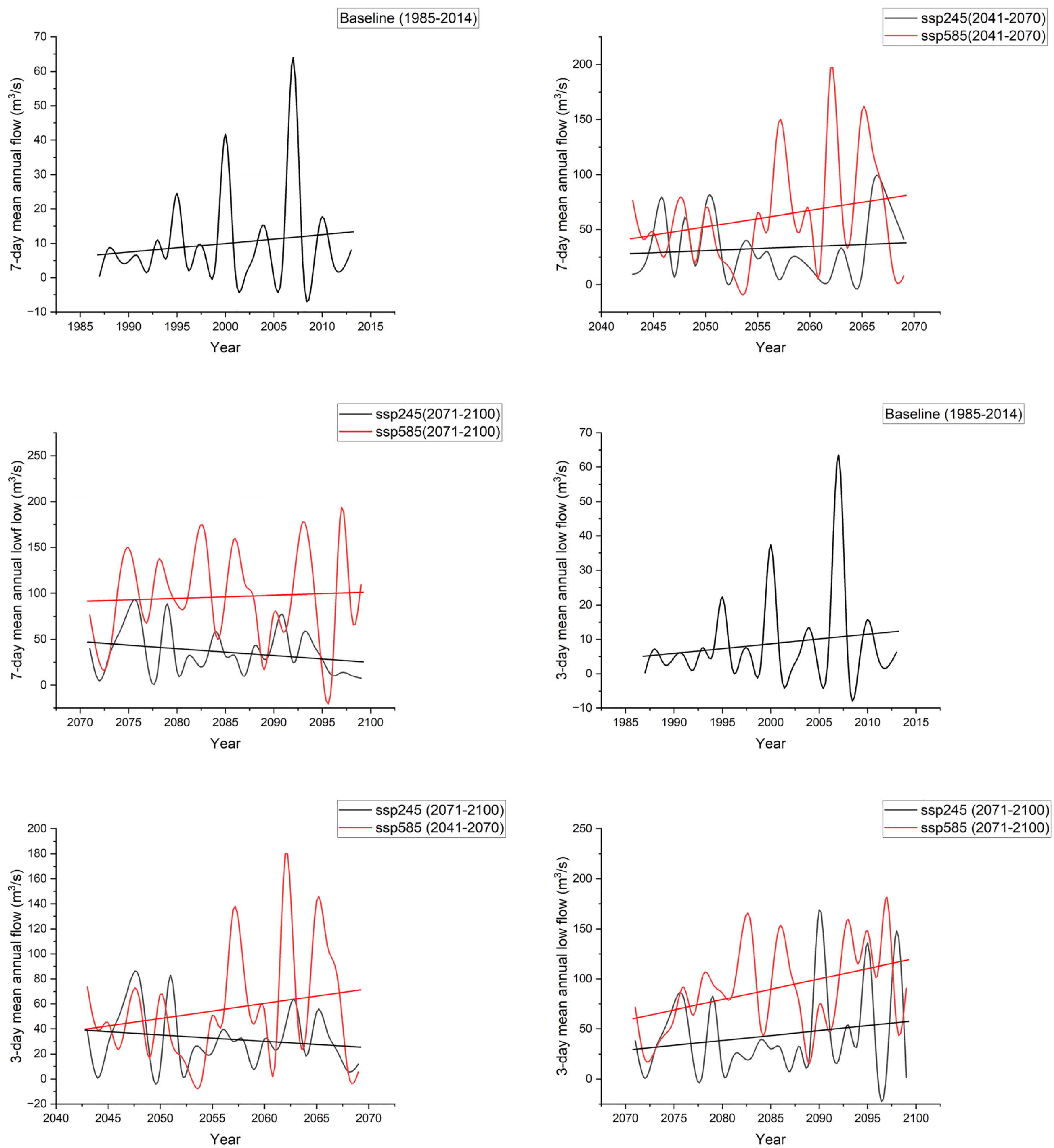

Fig. 8 3-day and 7-day annual minimum flow trend for baseline, SSP2-4.5, and SSP5-8.5 periods

both the baseline period and the future scenarios (SSP2-4.5 and SSP5-8.5) (Table 7).

In general, the impact of climate change on the timing of hydrological extremes has gained substantial attention among researchers, with multiple studies providing evidence of this phenomenon (Byun et al. 2019; Shrestha et al. 2021; Muñoz et al. 2023; Peters et al. 2023). These studies have indicated that there will be a shift in the timing of low flow and peak flow with climate change in the future. However, it should be noted that the amount of projected shift in the timing of low flow and peak flow can vary depending on the specific climate scenarios selected for the study (Francisco et al. 2023; Ye et al. 2023).

Table 6 Annual maximum 7 day and 30 day event days under (a) SSP2-4.5 and (b) SSP5-8.5

(a)

Event days	Scenario		
	Historical	SSP2-4.5(2041–2070)	SSP2-4.5(2071–2100)
7 day AMAX_Event Day	263.9	261.8	238.7
30-day AMAX_Event Day	275.5	280.4	268.3

(b)

Event days	Scenario		
	Historical	SSP5-8.5(2041–2070)	SSP5-8.5(2071–2100)
7 day AMAX_Event Day	263.9	273.1	265.5
30 day AMAX_Event Day	275.5	287.8	281.6

Table 7 Annual minimum 7 day and 30 day event days under (a) SSP2-4.5 and (b) SSP5-8.5

(a)

Event days	Scenario		
	Historical	SSP2-4.5(2041–2070)	SSP2-4.5(2071–2100)
7 day AMIN_Event Day	64.3	58.6	53.6
30 day AMIN_Event Day	65.9	64.8	61

(b)

Event days	Scenario		
	Historical	SSP5-8.5(2041–2070)	SSP5-8.5(2071–2100)
7 day AMIN _Event Day	64.3	81.8	69.1
30 day AMIN _Event Day	65.9	89.4	77.6

Conclusion and recommendation

In this study, the impact of climate change on the magnitude and timing of hydrological extremes was investigated. The SWAT+ model performed well for streamflow simulation during the calibration and validation periods, achieving NSE values of 0.83 and 0.74, respectively. GCM climate data from CMIP6 climate models were downscaled and bias-corrected before simulating the flow for the future scenarios of SSP2-4.5 and SSP5-8.5.

The results showed an increase in flow magnitude, with an annual average change of 12.8% for the SSP2-4.5 scenario and 29.9% for the SSP5-8.5 scenario relative to the baseline. Moreover, the study assessed the impact of climate change on both peak and low flows. Peak flow displayed an increasing trend in magnitude under both scenarios. For instance, the annual 7 day maximum flow exhibited changes of 22.3% and 40.1% under SSP2-4.5 and SSP5-8.5, respectively, compared to the baseline, while the low flow did not demonstrate a distinct trend.

Additionally, this study examined the influence of climate change on the timing of hydrological extremes. The findings revealed that the annual maximum 7 day event occurs between days 261 and 238 under the SSP2-4.5 scenario and between days 273 and 265 under the SSP5-8.5 scenario. Similarly, the timing of low-flow events is estimated to occur between days 53 and 58 under SSP2-4.5 and between days 69 and 81 under SSP5-8.5. In general, an earlier occurrence of events was observed for SSP2-4.5, while a later occurrence was noted for SSP5-8.5, for both low and peak flows compared to the baseline.

Overall, this study observed shifts in both magnitude and timing under climate change in the BRB. Nevertheless, it is crucial to acknowledge that hydrological extremes could be influenced by various factors beyond climate change alone. Therefore, future research should consider incorporating additional elements such as anthropogenic influences and inherent landscape features that can impact both the magnitude and timing of hydrological extremes.

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Author contributions
SMK conceptualized the study, conducted data analysis and wrote the manuscript, editing. TT and GT review, editing and supervision, ATH Review and editing. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
The authors have no competing interests to declare.

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