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Research Article

Evaluation of Future Climate and Potential Impact on Streamflow in the Upper Nan River Basin of Northern Thailand

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Water resources in Northern Thailand have been less explored with regard to the impact on hydrology that the future climate would have. For this study, three regional climate models (RCMs) from the Coordinated Regional Downscaling Experiment (CORDEX) of Coupled Model Intercomparison Project 5 (CMIP5) were used to project future climate of the upper Nan River basin. Future climate data of ACCESS_CCAM, MPI_ESM_CCAM, and CNRM_CCAM under Representation Concentration Pathways RCP4.5 and RCP8.5 were bias-corrected by the linear scaling method and subsequently drove the Hydrological Engineering Center-Hydrological Modeling System (HEC-HMS) to simulate future streamflow. This study compared baseline (1988–2005) climate and streamflow values with future time scales during 2020–2039 (2030s), 2040–2069 (2050s), and 2070–2099 (2080s). The upper Nan River basin will become warmer in future with highest increases in the maximum temperature of 3.8°C/year for MPI_ESM and minimum temperature of 3.6°C/year for ACCESS_CCAM under RCP8.5 during 2080s. The magnitude of changes and directions in mean monthly precipitation varies, with the highest increase of 109 mm for ACESSS_CCAM under RCP 4.5 in September and highest decrease of 77 mm in July for CNRM, during 2080s. Average of RCM combinations shows that decreases will be in ranges of −5.5 to −48.9% for annual flows, −31 to −47% for rainy season flows, and −47 to −67% for winter season flows. Increases in summer seasonal flows will be between 14 and 58%. Projection of future temperature levels indicates that higher increases will be during the latter part of the 20th century, and in general, the increases in the minimum temperature will be higher than those in the maximum temperature. The results of this study will be useful for river basin planners and government agencies to develop sustainable water management strategies and adaptation options to offset negative impacts of future changes in climate. In addition, the results will also be valuable for agriculturists and hydropower planners.

1. Introduction

The industrial revolution in 1880s and advancements of science and technology thereafter led to intensive rates of fossil fuel burning and indiscriminate use of natural resources. These activities are the main reasons for the atmospheric warming experienced since the late 20th century [1, 2]. The concentration of carbon dioxide gas in the atmosphere reached groundbreaking 414.5 parts per million in April 2020 escalating from 280 ppm recorded in 1880s. It is highly certain that these concentrations will further increase in future creating warmer atmospheric conditions [2–5]. International summits and meetings have been held with the participation of global leaders, aimed to discuss on reducing future greenhouse gas (GHG) emissions [6]. The warmer temperatures will increase water-holding capacity of air resulting in higher moisture contents, thereby creating intense rainfall and snow events [7]. The warming climate will accelerate the hydrological cycle, with changes in water balance components altering rainfall patterns and magnitude and timings of runoff. The changes in rainfall patterns are dynamic in space and time [8]. The changes in climates will create additional stress on water resources in many parts of the world [9]. The severity of the impacts varies, depending on local climate, topographical features, and the structure of water resource systems [10]. Regional and global changes in climates will affect all aspects of modern humanity including hydrology [11], hydropower generation [10, 12], agriculture [13], food security [14], human health [15], ecosystems [16, 17], groundwater [18], irrigation water requirements [19], and crop yield [20, 21].

The water availability in tropical regions is expected to change adversely due to the profound impacts of climate change [2]. Among these regions, Southeast Asia is highly vulnerable to climate change due to the region's high dependence of economy on agriculture and water resources [22, 23]. Due to the large complexities in climates of Asia, accurate regional-scale climatic projections are essentially required for this region [24]. Thailand was ranked among the first ten countries worst affected by climatic extremes in 2017 [25]. Significant changes in rainfall patterns, atmospheric temperature, and increased frequency of extreme climatic events were observed recently in Thailand [26, 27]. IPCC [2] claims that changes in temperature and precipitation levels due to climatic change were the prime reason for floods and droughts that recently happened in the country [28–30]. The northern part of Thailand is particularly vulnerable to climate change mainly due to its fragile agroecosystem, inhabited by a resource-poor population [31].

Although many factors affect changes in streamflow, precipitation and temperature are the two dominant factors affecting streamflow in the catchment scale [32]. Due to significant impacts of climate change on hydrology, the hydrologists are keen to evaluate the impacts of climate change on streamflow in regional and local scales. Hence, many researchers including Githui et al. [33], Candela et al. [34], Ali-Safi and Sarukkalige [35], Demaria et al. [36], Salis et al. [37], and Pandey et al. [38] used climate models under different GHG emission scenarios to drive hydrological models to explore the effects of climate change. These studies indicated that severity and magnitude of the impact due to climate change on streamflow depend on the geographical area and context. Hydrologic models driven by global climate model (GCM) projections can be used to investigate possible impacts of future climate on hydrology [39]. However, GCMs limit the accurate simulations of regional climatology due to the inability in accurately simulating features of local climate including topography, cloudiness, orography, and land use due to the inherent coarse resolution ranging between 100 and 250 km [40–42]. Hence, increased tendency is witnessed in applications of regional climate models (RCMs) combined with hydrological models to examine the impact of climate change on hydrology [43]. The resolution of these RCMs is in the range of 12 to 50 km, in proximity of the watershed scale. Yet, RCM-projected climatic variables should be handled with caution since they consist of significant biases due to imperfect conceptualization, internal climatic variability, discretization, and spatial averaging within grid cells [44–46]. These factors limit direct applications of RCMs into hydrological models. GHG emission scenarios based on demographic growth, socioeconomic development, and technological growth add an uncertainty into climate change impact assessments [41]. Usage of multiple RCMs or GCMs under several Representative Concentration Pathways (RCPs) aiming at reducing uncertainties has been carried out in many studies including Minville et al. [47], Xu et al. [48], Nkomozepi and Chung [49], Agarwal et al. [50], Jha et al. [51], Jha and Gassman [52], and Babur et al. [53]. Furthermore, multimodel ensembles have also been encouraged by the Intergovernmental Panel on Climate Change (IPCC) [54]. Multiple GCMs or RCMs combined with several emission scenarios, downscaling methods, and bias correction methods are recommended for climate change modeling studies.

In Thailand, several studies attempted to project future climate and evaluate the impact of future-climate soil erosion [55–57], reservoir inflows [58], rice production [59, 60], irrigation water requirements [61], future precipitation extremes [62], monsoon seasonal precipitation [63], and groundwater [64, 65]. In addition to these studies, Shrestha et al. [66], Sharma and Babel [67], Sharma and Babel [68], Supakosol and Kangrang [69], Sangmanee et al. [70], Ponpang-Nga and Techamahasaranont [71], Deb et al. [72], and Shrestha [73] attempted to evaluate the impact of climate change on streamflow in the basin scale and national level of Thailand. Plangoen and Babel [57] and Plangoen et al. [56] projected future climate based on the Special Report on Emission Scenarios (SRES) of Coupled Model Intercomparison Project 3 (CMIP-3) [74] to evaluate the impact on rainfall erosivity in upper Nan. Hence, the present study is the first study which modeled the upper Nan River basin (UNRB) with the Hydrological Engineering Center-Hydrological Modeling System (HEC-HMS) [75] with the latest GHG emission scenarios from RCPs and climate models from CMIP 5. Reliable estimates of the impact of future climate on hydrology are imperative to formulate adaptation measures to enhance water security and to promote sustainable water management strategies, especially for a developing nation such as Thailand. Acknowledging the needs of fine-scale climate model simulations, three RCMs from the Coordinated Regional Downscaling Experiment (CORDEX) under RCP4.5 (medium-level GHG emission scenario) and RCP8.5 (high-level GHG emission scenario) were used to project future climate in the UNRB in this study. The bias-corrected future climate was then used to drive the HEC-HMS model to investigate the potential impact of future climate on streamflow. Thereafter, the projected future climate and streamflow in near future (2020–2039), midfuture (2040–2069), and far future (2070–2099) were analyzed and compared with baseline conditions (1988–2005) for monthly, seasonal, and annual scales.

The structure of the remaining parts of the paper is organized as follows. The second section provides a detailed description of the study area, data used for this study, and subsequently, the research methodology. Results and discussion of the study are discussed through the third section.

The summary, outcomes, and conclusions of this work are discussed in the fourth section of this paper.

2. Materials and Methods

2.1. Study Area. Figure 1 provides the distribution of rainfall gauging, meteorological, and streamflow stations in the upper Nan River basin.

The upper Nan River basin (UNRB) is located between 100°06′30″–101°21′48″E and 17°42′12″–19°37′48″ N in Northern Thailand. It is one of the four major subbasins of the greater Chao Phraya basin [76]. The UNRB drains a geographical area of 13,000 km^2 [77]. A high amount of rainfall is normally received during July and August [56]. The climate of this region is tropical monsoon and has three well-defined seasons: a rainy season or southwest monsoon season (from mid-May to late-Oct), a winter season with a relatively dry climate (from early-Nov to late-Feb), and a summer season of relatively warmer temperature levels (from mid-Feb to mid-May). The mountainous regions in the north of the UNRB receive an annual rainfall of more than 1000 mm, while the relatively flat regions in the middle receive a rainfall between 600 and 1000 mm. Nearly, 80% of the annual rainfall which is received during the rainy season is delivered by the southwest monsoon developed in the Indian Ocean [56]. The average annual temperature variation is between 20 and 34°C in the UNRB [77, 78].

The topographical variation, soil cover, and land use of the UNRB are illustrated through Figures 2(a)–2(c), respectively. The elevation ranges between 0 and 2020 m above mean sea level. The dominant soil type is slope complex which is often found in forested steep slopes having low permeability rates [79]. The other main soil types found in the UNRB are of silty clay and clay loam nature in Hang Chat and Mae Rim. Nakom Pathom is fine textured [77]. Mae Sai is of poorly drained medium-textured type soils [80]. The forested mountain areas and highlands are dominated in the upper part covering nearly eight five percent of the land area. Forests and agricultural lands account for 71 and 15% of the total land area. The rest of the land comprises grasslands, water bodies, and urban areas. The UNRB provides livelihood for 477,000 inhabitants of indigenous communities [79]. Importantly, the UNRB provides home for 108 fish species amounting 600 types found in Thailand [81].

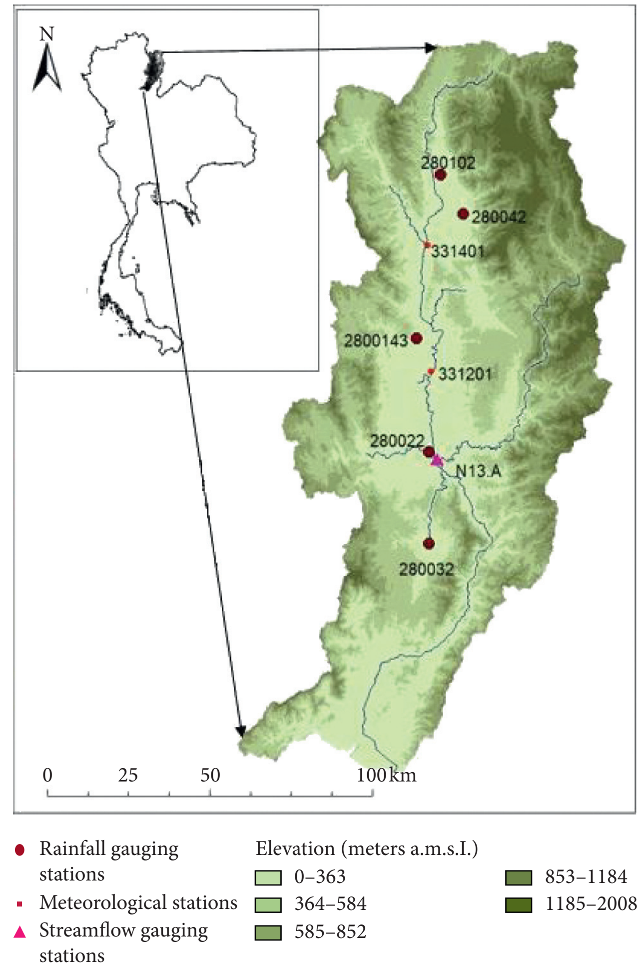


Figure 1: Rainfall stations, meteorological stations, and streamflow stations in the upper Nan River basin of Northern Thailand.

2.2. Data. Table 1 presents the temporal and spatial data used in this study. Detailed information of observed, gridded climatic datasets, climate models used for future climate projections, and spatial datasets used is given.

Daily temperature and rainfall records at two meteorological stations with corresponding station IDs 331201 (Nan Meteorological Station) and 331401 (Tha Wang Pha) were obtained from the Thai Meteorological Department (TMD). Daily rainfall data records at five rain gauging stations with station IDs 280022 (Wiang Sa station), 280032 (Na Noi station), 280042 (Pua station), 280102 (Chiang Klang station), and 280143 (Nan Agrometeorological Station) were obtained from the Royal Irrigation Department (RID) of Thailand. All climatic data records were obtained for 1976–2014. In addition, observed daily streamflow data during 1988–2014 at station N.13A (Ban Bun Nak, Wiang Sa station) were obtained from the RID. Furthermore, gridded rainfall data from Climate Prediction Center Global Precipitation (CPC-GP) datasets (available at https://climatedataguide.ucar.edu/) developed by the National Oceanic and Atmospheric Administration Earth System Research Laboratory (NOAA-ESRL) which showed a fairly good correlation with observed data were used to fill missing rainfall days in some of the rain gauging stations.

The digital elevation model (DEM) of resolution 150 m × 150 m was obtained from the Royal Thai Survey Department (RTSD). A land use map of 500 m resolution and a scale of 1 : 50,000 and soil cover map with 1 km resolution and a scale of 1 : 100,000 for the year 2010 were obtained from the Land Development Department (LDD) of Thailand.

Three RCMs, ACCESS_CCAM, MPI_ESM_CCAM, and CNRM_CCAM from CORDEX platform developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) under RCP4.5 and RCP8.5, were used to project

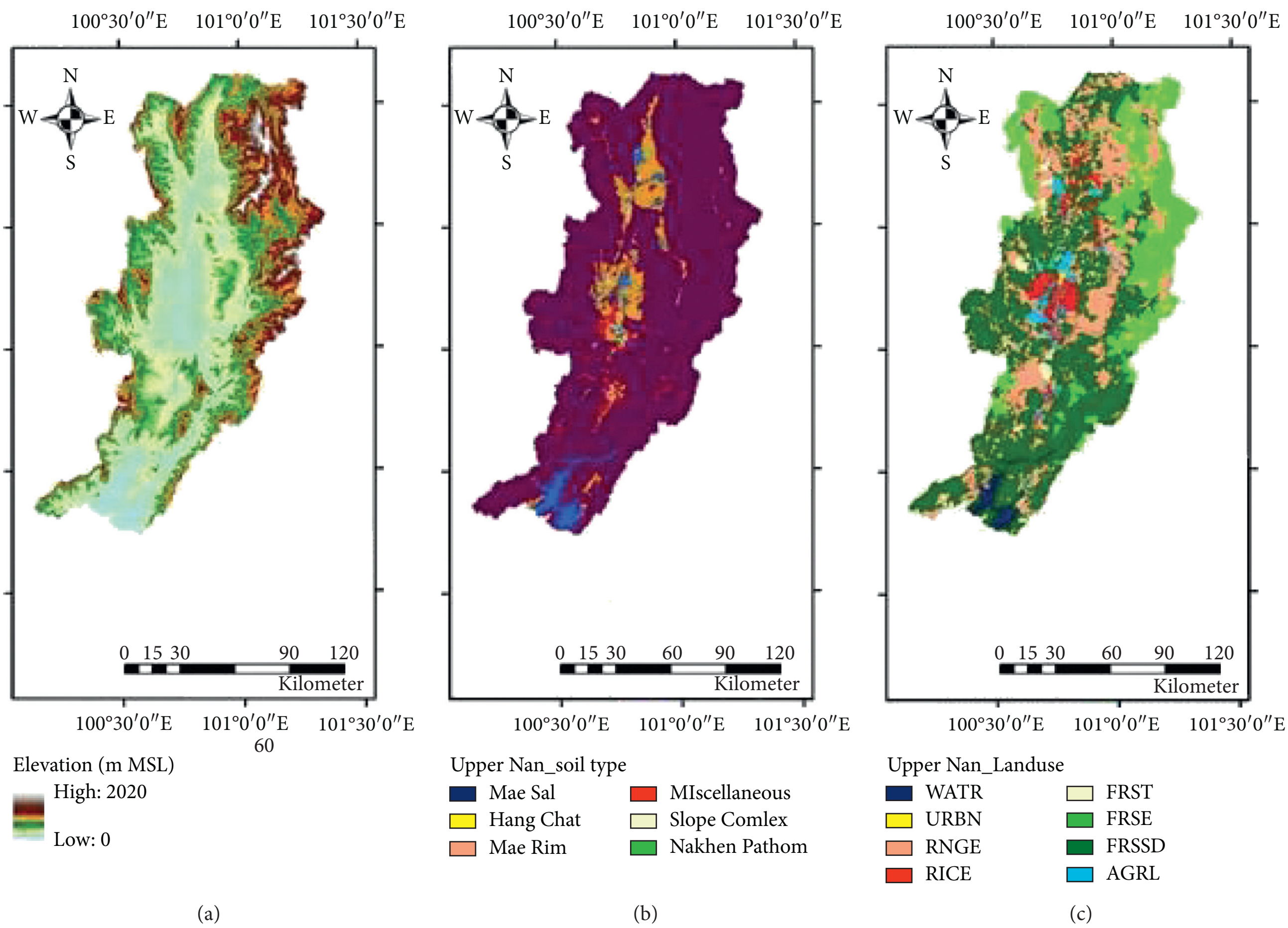


Figure 2: (a) Topography, (b) soil cover, and (c) land use in the upper Nan River basin.

Table 1: Temporal and spatial data used.

Data	Spatial/temporal resolution	Source
Temporal datasets		
Observed temperature	Point/daily	TMD
Observed rainfall	Point/daily	TMD and RID
Gridded rainfall	$0.5^{\circ} \times 0.5^{\circ}$/daily	NOAA-ESRL
Observed streamflow	Point/daily	RID
Spatial datasets		
Topography	150 m × 150 m	RTSD
Soil cover	500 m × 500 m	LDD
Land use	90 m × 90 m	LDD
RCMs under RCP4.5 and RCP8.5		
RCM	Spatial/temporal resolution	Contributing CORDEX modeling center
ACCESS_CCAM	$0.5^{\circ} \times 0.5^{\circ}$/daily	CSIRO
MPI_ESM_CCAM	$0.5^{\circ} \times 0.5^{\circ}$/daily	CSIRO
CNRM_CCAM	$0.5^{\circ} \times 0.5^{\circ}$/daily	CSIRO

future climate. The driving GCMs of these RCMs are ACCESS 1.0, MPI_ESM_LR, and CNRM_CM5, respectively. The grid domain of RCMs used was CORDEX South Asia 1391M. The units of precipitation and temperature in CORDEX are mm and K, respectively. RCMs from CORDEX [38, 82] of 50 km resolution were used in this study. The climatic data availability of RCMs was 1976–2100 comprising a historical period between 1976 and 2005 and a future period between 2006 and 2100. ACCESS_CCAM, MPI_CCAM, and CNRM_CCAM are referred to as ACCESS, MPI, and CNRM hereafter in the text.

2.3. HEC-HMS Model Description. The HEC-HMS model developed by the United States Army Corps of Engineers is a conceptually based model which can perform event-based and long-term simulations [75]. This study used HEC-HMS 4.3. The HEC-HMS model consists of four model components: the basin model, the meteorological model, time specification model, and the input data model. The HEC-HMS offers 11 precipitation loss, 7 direct runoff, 5 baseflow, and 6 routing methods. In addition, the model also simulates canopy, surface, and loss/gain mechanisms. More details on the development of the model can be found in Pinto [83],and in the studies of Feldman [75] and Scharffenberg and Fleming [84]. Availability in the public domain and user-friendly geographical information system has resulted in extensive applications in different regions of the world. The HEC-HMS model has been used in studies related to climate change impact assessment on streamflow [85, 86], reservoir spillway capacity studies [87], urbanization impact on hydrology [88], and operationalizing a flood forecasting decision support system [89].

2.4. Coordinated Regional Downscaling Experiment (CORDEX). The CORDEX, an initiative of the World Climate Research Program, aimed at regional climate modeling through dynamically downscaled Coupled Model Intercomparison Project 5 (CMIP5) Atmospheric-Ocean General Circulation Model outputs using multiple RCMs. CORDEX climate datasets are available at https://www.cordex.org/. The RCPs are four greenhouse gas emission concentration trajectories adopted by the IPCC [2]. The four RCPs, RCP2.5, RCP4.5, RCP6.0, and RCP8.5, are named after a possible range of radiative forcing values relative to preindustrial levels. More details on RCP scenarios can be found in Van Vuuren et al. [90]. Different RCPs relate to the radiative forcing, which is a measure of overall change in the Earth's energy balance due to external perturbation [2]. CORDEX climatic data had been previously used for climate change studies by Sharannya et al. [43], Endris et al. [91], Solman [92], Virgilio et al. [93], and Prein et al. [94] in Asia, South America, Europe, North America, Africa, and Australia.

3. Methodology

3.1. Watershed Model Development. In this study, the DEM was fed into the Hydrological Engineering Center-Geospatial Hydrological Modeling Extension tool in the Arc Geographical Information System to develop the basin model. Watershed characteristics such as river length, basin slope, basin centroid, elevation of basin centroid, flow directions, and streamlines were automatically calculated through this process. The areal rainfall distributions were calculated by the Thiessen polygon method [95]. Manual calibration was performed by satisfying the goodness-of-fit criterion by maximizing Nash–Sutcliffe efficiency (NSE) between observed and simulated discharges. It was ensured that a physically meaningful set of parameters were fixed between the ranges outlined by Feldman [75]. The hydrological model developed through this study was calibrated at station N13.A operated by the RID which drains a geographical area of 8573 km^2. The watershed model was calibrated between 1988 and 2004 (17 years) and validated between 2005 and 2014 (10 years). The precipitation losses, direct runoff transformation, baseflow, and routing were simulated by the soil moisture accounting method, Clark unit hydrograph, recession method, and Muskingum methods [75].

The soil moisture accounting method was used in conjunction with canopy and surface methods. Interested readers are encouraged to refer Ouédraogo et al. [96] and De Silva et al. [97] for detailed information on the soil moisture accounting method. Maximum infiltration which reflects the hydraulic conductivity and GW1 percolation rate (refer Table 2) were adjusted based on the properties of soil distributed in the study area. All other parameters were adjusted based on the trial-and-error method. Table 2 provides the final calibrated values used in the soil moisture accounting method. The values of parameters in direct runoff transformation, baseflow, and routing were fixed based on the guidelines of De Silva et al. [97], Pinto [83], Scharffenberg and Fleming [84], and Feldman [75].

3.2. Future Climate Projection and Analysis. This study used three RCMs of the CORDEX as mentioned earlier in Section 2.2. The selection of RCMs used to project future climate in the UNRB was based on their representativeness of simulating climate in Thailand and the Southeast Asian region previously reported by Shrestha et al. [66], Adhikari et al. [98], Shrestha et al. [99], Shrestha et al. [100], Shrestha et al. [101], and Shrestha et al. [66]. The ensemble mean method calculated by simple arithmetic average [102] was used to assess the future climate in the UNRB which was previously used by Shrestha et al. [103] and Bhatta et al. [8]. Furthermore, the bias-corrected future climate was analyzed under three time windows. The future time period was sliced as near future (2020–2040), midfuture (2041–2069), and far future (2070–2099).

3.3. Bias Correction of Rainfall and Temperature. Bias correction methods are used to remove biases in future climatic data due to imperfect conceptualization, internal climatic variability, discretization, and spatial averaging within grid cells [44]. Bias correction can be done through linear scaling, local intensity scaling, variance scaling, distribution mapping, power transformation, quantile mapping, and delta change [104]. Readers are encouraged to refer Teutschbein and Seibert [39] for detailed information on these methods. Bias correction can also be applied to other meteorological variables such as relative humidity, solar radiation, and wind speed [105]. The bias of future climate of RCMs was removed by using observed data compared with the raw hindcast climate of RCMs (1976–2005).

The linear scaling method (LS) [106] is used in this study to remove biases in climate data. The linear scaling approach assumes that correction algorithm and parameterization of historical climate will remain stationary for future climatic conditions. Climate studies carried out in different regions of the globe demonstrate that the LS approach performs well

Table 2: Calibrated values of parameters of the soil moisture accounting model.

Parameter	Value
Soil (%)	70
Ground water 1 (%)	45
Ground water 2 (%)	82
Max infiltration (mm/hr)	10
Imperviousness (%)	20
Soil storage (mm)	125
Tension storage (mm)	75
Soil percolation (mm/h)	0.75
Ground water 1 storage (mm)	100
Ground water 1 percolation (mm/h)	1
Ground water 1 coefficient (h)	100
Ground water 2 storage (mm)	150
Ground water 2 percolation (mm/h)	1
Ground water 2 coefficient (h)	1

for coarse temporal scale analysis as more complicated methods such as quantile mapping, delta change, and power transformation [107, 108]. Equations for bias correction in precipitation are provided by equations (1) and (2) and for temperature by equations (3) and (4). In this study, the performance of the linear scaling method is evaluated using three statistical indicators: coefficient of determination (R^2), root mean square error (RMSE), and standard deviation (SD). Higher R^2, lower RMSE, and close SD to those of observed data indicate improved performance after bias correction [109, 110]. The linear scaling correction was applied at individual stations.

$$P_{*\mathrm{his}}(d) = P_{\mathrm{his}}(d) \times \left[\frac{\mu_m\left(P_{\mathrm{obs}}(d)\right)}{\mu_m\left(P_{\mathrm{his}}(d)\right)}\right], \tag{1}$$

$$P_{*\mathrm{sim}}(d) = P_{\mathrm{sim}}(d) \times \left[\frac{\mu_{\mathrm{m}}\left(P_{\mathrm{obs}}(d)\right)}{\mu_{\mathrm{m}}\left(P_{\mathrm{his}}(d)\right)}\right], \tag{2}$$

$$T_{*\mathrm{his}}(d) = T_{\mathrm{his}}(d) + \left[\mu_{\mathrm{m}}\left(T_{\mathrm{obs}}(d)\right) - \mu_{\mathrm{m}}\left(T_{\mathrm{his}}(d)\right)\right], \tag{3}$$

$$T_{*\mathrm{sim}}(d) = T_{\mathrm{sim}}(d) + \left[\mu_{\mathrm{m}}\left(T_{\mathrm{obs}}(d)\right) - \mu_{\mathrm{m}}\left(T_{\mathrm{his}}(d)\right)\right]. \tag{4}$$

The notations used in equations (1)–(4) are given as follows.

μ_{m}: long-term monthly mean; $*$: bias-corrected; his: raw RCM hindcast; obs: observed data; sim: raw RCM corrected; P: precipitation; T: temperature; d: daily.

3.4. Evaluation of the Impact of Future Climate on Streamflow. Climate change impact on streamflow was analyzed under annual, monthly, and seasonal scales with respect to the baseline period. In addition to that, flow quantiles (Q5, Q50, and Q95) were also calculated using FDC software available at https://www.hydrooffice.org/Tool/FDC). Detailed analysis of different flow-related indices will allow studies related to drought and hydropower operations. Q5 is low flow, Q50 is median flow, and Q95 high flow. Determination of the future flow duration curve will be important for designing and improving structures of reservoirs and hydropower plants.

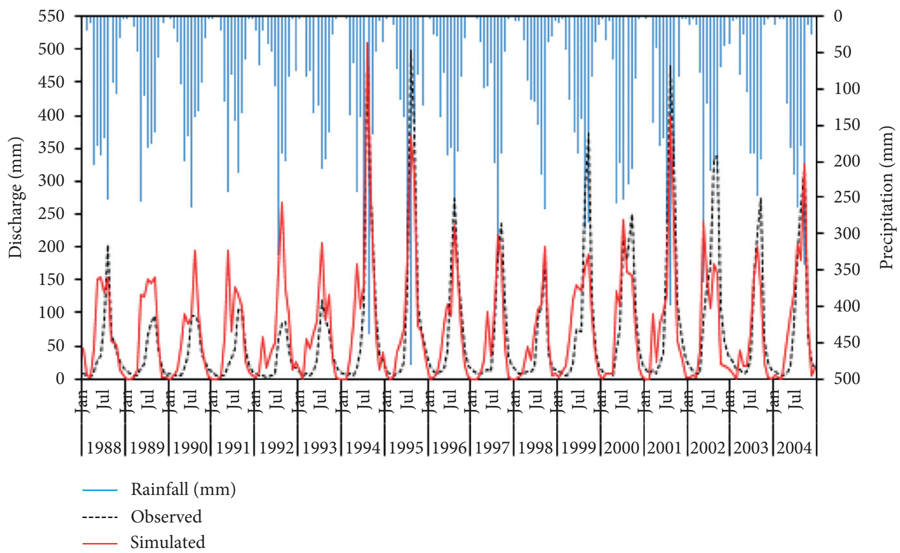
4. Results and Discussion

4.1. Hydrological Model Development. The monthly hydrographs obtained during calibration and validation at streamflow gauging station N.13A (refer Figure 1) are illustrated through Figures 3(a) and 3(b). The flow hydrographs are given in the format of discharge per drainage area (units in mm) for easy comparison to the corresponding rainfall. The visual comparisons and statistical indicators strongly inferred that the developed HEC-HMS model is capable of tracking monthly streamflow of the upper Nan River basin reasonably well although, with few discrepancies. However, increases in rainfall through 1988–1993, 2009, and through 2012–2014 did not produce any relative changes in observed discharge rates. These mismatches might be due to localized storm events. Coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), and percentage error in volume (P.E.V.) were 0.68, 0.67, and 12.89% and 0.71, 0.70, and 7.4% during calibration and validation, respectively. The performance of the developed hydrological model is acceptable [111]. The model accurately captured peaks in 1997-1998, 2000 and 2004, and 2005 and 2008 with a reasonable accuracy. However, some peaks were slightly ahead of time, while some peaks were slightly late in time. Since there is a good agreement between observed and simulated flows, the calibrated model is adequate to simulate the availability of water resources in the long-term run.

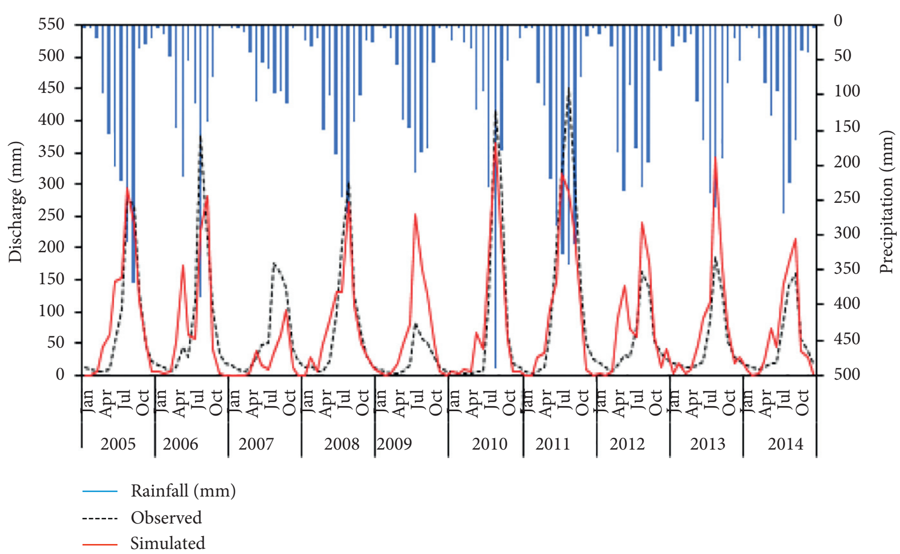
4.2. Future Climate Projections. The bias-corrected future climate of ACCESS, CNRM, and MPI was examined under three time windows with reference to baseline as mentioned earlier in Section 2.2. However, before future projections, the performance of the linear scaling method was examined. The hindcast RCM data were compared with observed historical data, and monthly correction factors were applied to raw RCM data as explained in Section 3.3. Increased R^2 (coefficient of determination), decreased RMSE (root mean square error), and close standard deviations (SD) to observed data after bias correction have indicated the improved performance of the bias correction method. The ranges of statistical indicators used for evaluation of bias correction before are provided through Table 3.

Maximum temperature, minimum temperature, and precipitation are hereafter referred to as $T_{\max}$, $T_{\min}$, and P in the text. Baseline $T_{\max}$, $T_{\min}$, and P and changes with respect to 2030s, 2050s, and 2080s are given through Table 4.

Baseline average annual ensemble $T_{\max}$, $T_{\min}$, and P are 32.53°C, 20.41°C, and 1255 mm, respectively. The increases in average annual ensemble $T_{\max}$ are 0.86, 1.18, and 1.84°C



(a)



(b)

Figure 3: (a) Hydrographs during calibration (1988–2004) and (b) validation (2005–2014).

under RCP4.5 and 0.93, 1.88, and 3.02°C under RCP8.5 during 2030s, 2050s, and 2080s, respectively. The increases in average annual ensemble T_{min} are 0.42, 1.03, and 1.97°C under RCP4.5 and 0.73, 1.76, and 3.41°C under RCP8.5, respectively. Towards the end of the 20$^{\text{st}}$ century, increases in T_{min} are significantly higher compared to T_{max} with higher increases for RCP8.5. Figure 4 depicts the changes in temperature and precipitation levels under different RCMs under RCP4.5 and RCP8.5.

As seen through Figure 4, the trends in annual temperature (for both maximum and minimum) for all RCMs are unidirectional in increasing order. The highest increases will be during 2080s followed by 2050s and 2030s. Although annual ensemble temperature levels are steadily increasing, annual precipitation levels do not show fixed trends. The annual precipitation ensemble changes vary slightly within different time periods considered (−4.5 to 4.1%). Annual average rainfall will decrease in MPI for all time periods. Annual rainfall will decrease for all RCMs under RCP4.5 during 2030s. It is noteworthy that, under RCP8.5, during 2030s, all RCMs will decrease except ACCESS. With the exception in 2030s, precipitation projections in ACCESS will increase. Different directions and magnitudes in changes in RCMs indicate that there are a wide range of uncertainties associated in future climate projections.

Figure 5 illustrates the changes in ensemble temperature and precipitation in the monthly scale with respect to baseline conditions.

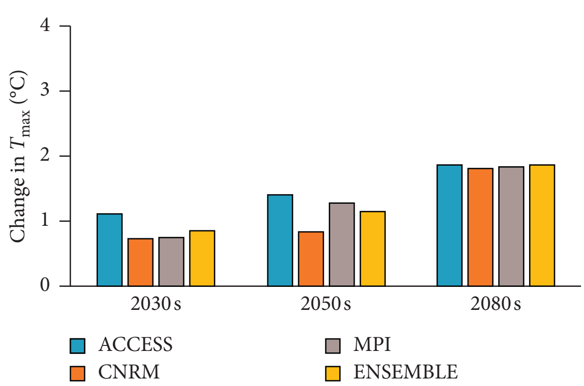
Highest increases of 4.2°C for T_{min} will be during November in 2080s under RCP8.5. Highest increase in T_{max} of 2.8°C will occur during August of 2080s under RCP8.5. It is noteworthy that a slight decrease in the minimum

Table 3: Results of bias correction.

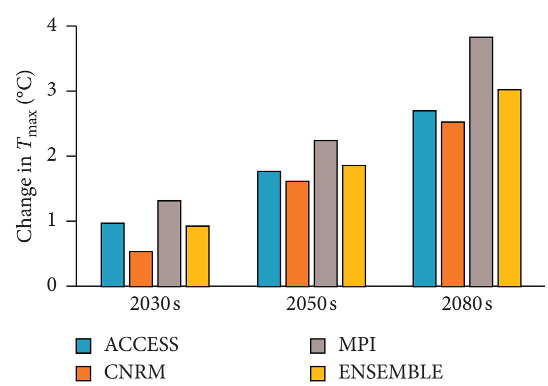
Variable	Statistical indicator	Raw	Bias-corrected
Maximum temperature	R^2	0.41–0.43	0.51–0.58
	RMSE (°C)	2.23–2.47	1.76–1.98
	SD (°C)	2.56–2.82	2.55–2.80
		Observed SD (°C) = 2.37–2.42	
Minimum temperature	R^2	0.67–0.68	0.84–0.86
	RMSE (°C)	2.30–2.51	1.56–1.65
	SD (°C)	3.78–4.22	3.87–4.25
		Observed SD (°C) = 3.92–4.24	
Precipitation	R^2	0.26–0.38	0.37–0.55
	RMSE (°C)	85.95–119.4	72.64–105.53
	SD (°C)	41.70–49.98	86.35–127.99
		Observed SD (mm) = 87.94–119.2	

Table 4: Projected changes in annual average ensemble maximum temperature (T_{max}), minimum temperature (T_{min}), and precipitation (P).

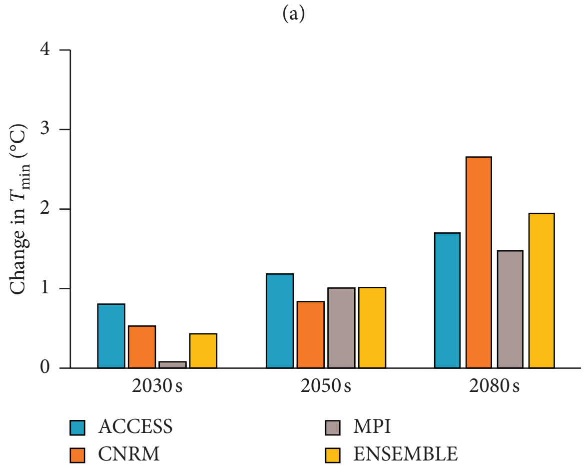
Time period	Baseline T_{max} (°C)	Change in T_{max} (°C)	Baseline T_{min} (°C)	Change in T_{min} (°C)	Baseline P (mm)	Change in P (mm)
RCP4.5						
	32.53		20.41		1255.0	
2030s		0.86		0.42		−56.84
2050s		1.18		1.03		22.16
2080s		1.84		1.97		47.05
RCP8.5						
2030s		0.93		0.73		−13.39
2050s		1.88		1.76		21.86
2080s		3.02		3.41		51.87



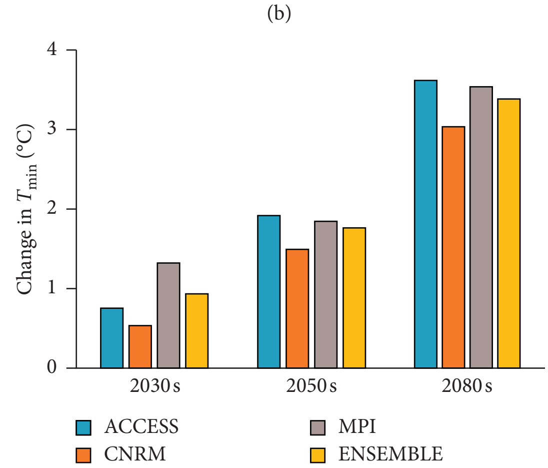
(a)



(b)



(c)



(d)

Figure 4: Continued.

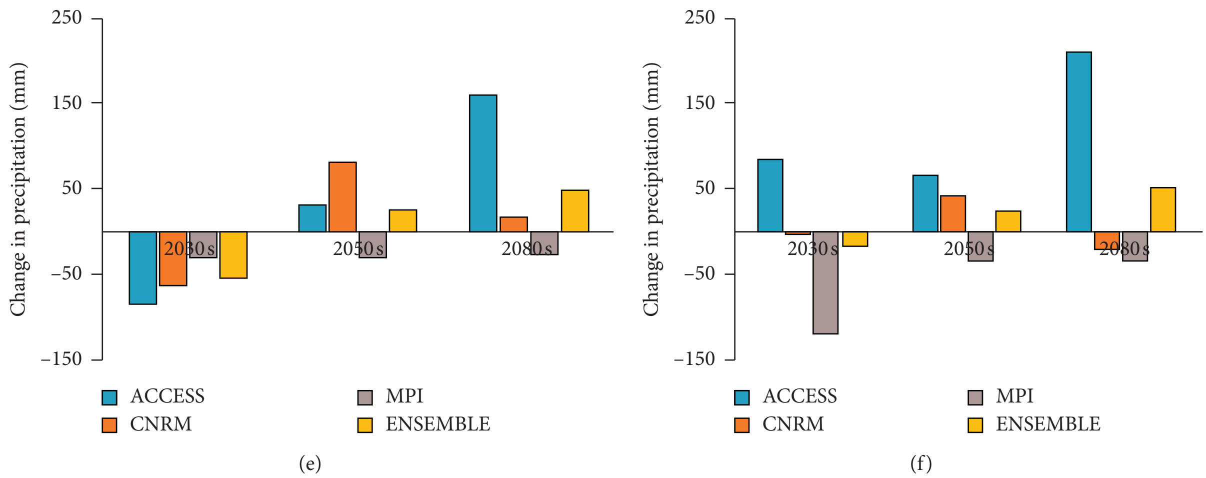


Figure 4: Temperatures and precipitation under RCP4.5 and RCP8.5. (a) For T_{max} under RCP4.5. (b) For T_{max} under RCP8.5. (c) For T_{min} under RCP4.5. (d) For T_{min} under RCP8.5. (e) For P under RCP4.5. (f) For P under RCP8.5.

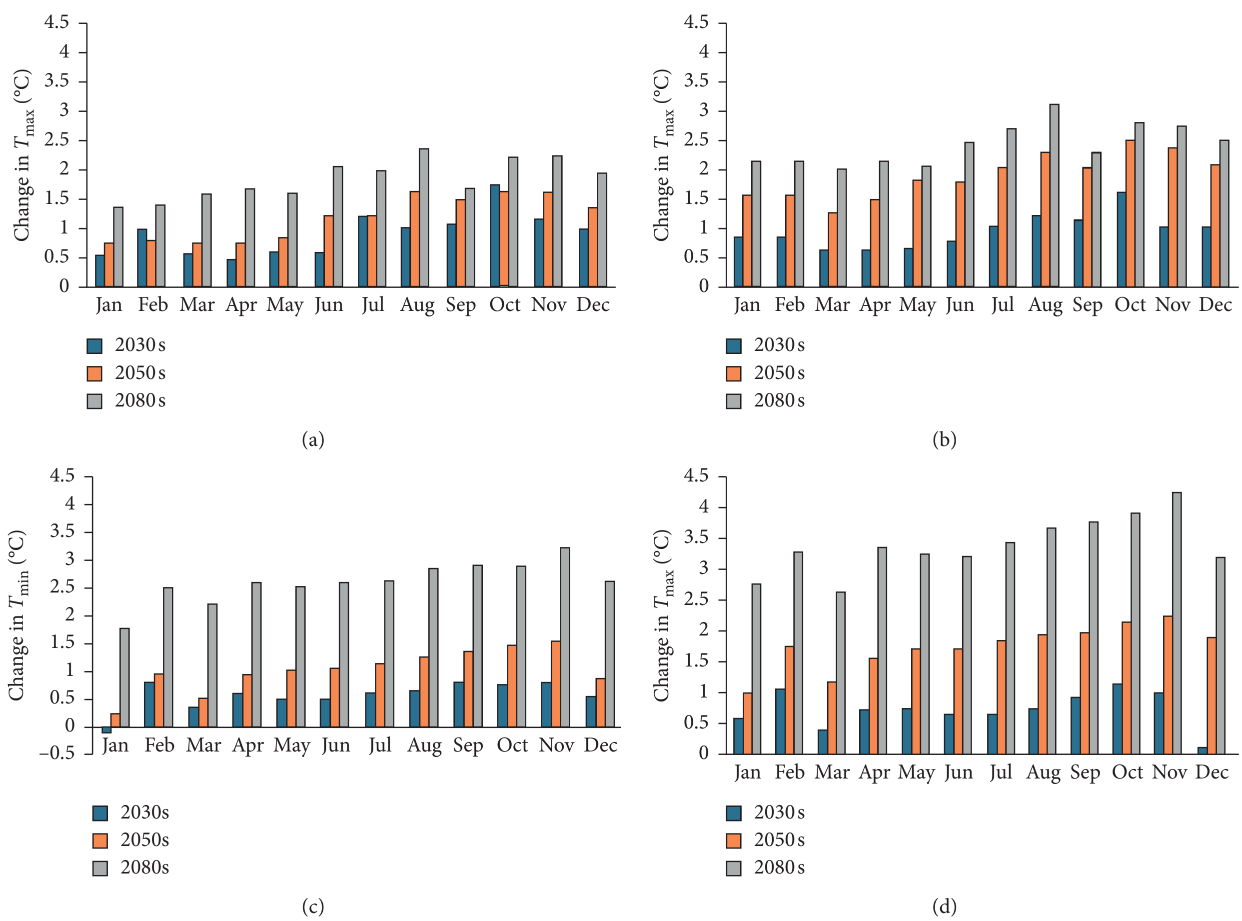
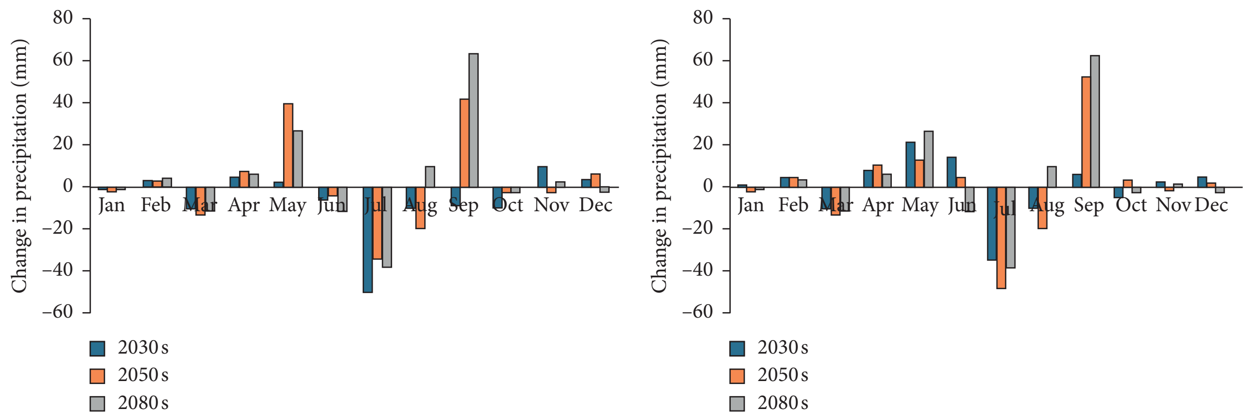
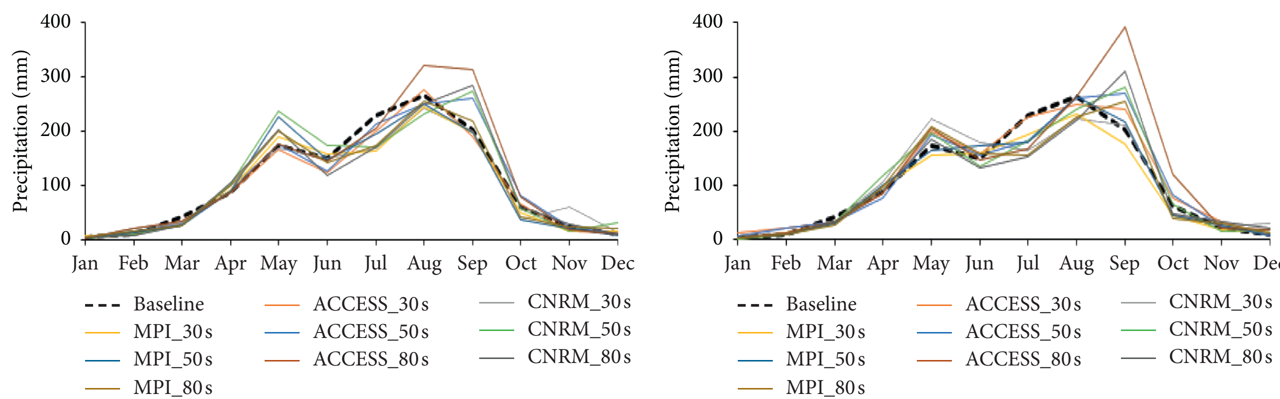


Figure 5: Continued.



(e) (f)

Figure 5: Changes in mean monthly ensemble. (a) For T_{max} under RCP4.5. (b) For T_{max} under RCP8.5. (c) For T_{min} under RCP4.5. (d) For T_{min} under RCP8.5. (e) For P under RCP4.5. (f) For P under RCP8.5.



(a) (b)

Figure 6: Mean monthly precipitations under different RCMs. (a) Under RCP4.5. (b) Under RCP8.5.

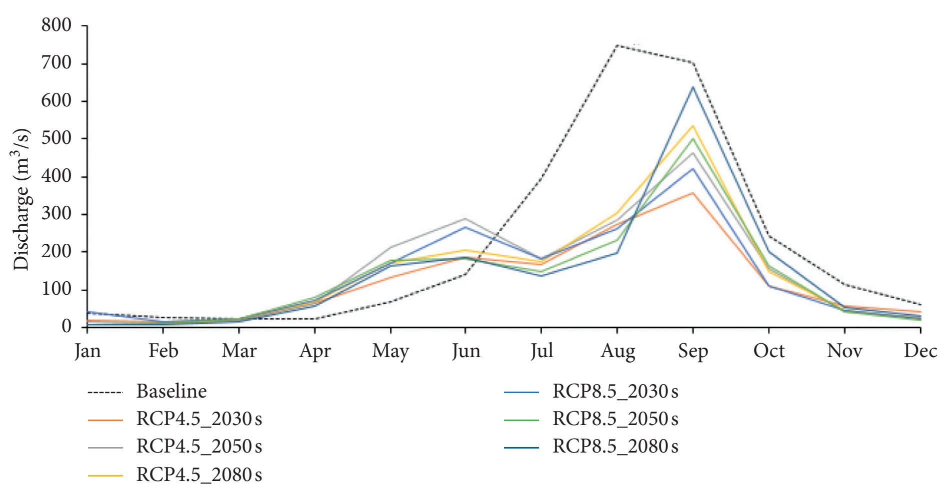


Figure 7: Ensemble mean monthly discharges under RCP4.5 and RCP8.5.

temperature during January is observed. However, minimum and maximum temperatures under both RCP4.5 and RCP8.5 show that increases in temperatures are in the ascending order along the timeline. In other words, Tmin in 2080s are the highest, while Tmin in 2050s are higher than 2030s.. The results of this study are consistent with previous studies carried out in the Southeast Asian region by Shrestha et al. [66], Aung et al. [110], and Trang et al. [112]. The ranges of increase in T_{max} under RCP4.5 in 2030s, 2050s, and 2080s ranged between (0.45–0.75°C), (0.8–1.7°C), and (1.4–2.4°C) under RCP8.5 (0.58–1.60°C), (1.3–2.5°C), and (2.03–3.1°C). For T_{min}, these changes were between (−0.08–0.83°C), (0.24–1.5°C), and (1.8–3.2°C) under RCP4.5 and (0.1–1.2°C), (1–2.3°C), and (2.7–4.2°C) under RCP8.5, respectively.

The highest ensemble increase of mean monthly precipitation is 109 mm during September under ACCESS, while the highest decrease is 77 mm in CNRM. Both highest increase and decrease are under RCP8.5 during 2080s. Increases in rainfall during February, April, and May and decreases during March and July will be expected under both scenarios. The variations in individual RCM projections are shown in Figure 6. The results indicate that the peak rainfall in future time periods can be expected in September in contrast to the current peak rainfall events reported in July and August.

4.3. Impact of Future Climate on Streamflow. Future climate impact on streamflow on annual, monthly basis, and seasonal scales was assessed. Since 85% of annual rainfall occurred during the rainy season, the other two seasons were less influential in streamflow. Due to significant contributions of rainfall during the rainy season, decreases in rainy season precipitation (as seen through Figure 5) will decrease annual streamflow. Significant decreases in streamflow in rainy seasons under both RCP scenarios have been observed in this Southeast Asian region by Shrestha et al. [66] and Kim et al. [113]. During the baseline period, daily average streamflow is 217 m^3/s, for the rainy season, this is 1080 m^3/s, for the summer season, this is 138 m^3/s, and for the winter season, this is 37 m^3/s. All RCMs under both emission scenarios decreased, while the highest decreases were in MPI in most of the cases. Average of RCM combinations shows that decreases in streamflow will be in ranges of −5.5 to −48.9% for annual flows, −31 to −47% for rainy season flow, and −47 to −67% for winter season flows. Increases in summer seasonal flows will be between 14 and 58%. The highest decreases for streamflows are in MPI (refer Figures A1 and A2 in Appendix in Supplementary Materials).

Figure 7 provides ensemble mean monthly discharges under RCP4.5 and RCP8.5. Mean monthly ensemble streamflow will decrease under all time horizons throughout July–February for RCP4.5 and RCP8.5. Increases in mean monthly ensemble streamflow will be in May-June of the rainy season. Increases will also be there in April and June of summer months. Decreases in streamflow will occur during the entire winter season (November–January). Flow duration curves for ensemble streamflow during 2030s, 2050s, and 2080s are given by Figure A3 for (a) RCP4.5 and (b) RCP8.5 in Appendix. The FDCs imply that decreases are anticipated in high flows while increases in low flows. The discharges corresponding to Q5, Q50, and Q95 are provided through Table A1 in Appendix in Supplementary Materials.

5. Conclusions

This study evaluated the future climate and its impacts on streamflow of the upper Nan River basin using three bias-corrected RCMs and the HEC-HMS hydrological model. The level of changes in precipitation and temperature varies within individual RCMs.

The expected reductions in streamflow rates will have adverse impact on many sectors including aquatic ecosystems, domestic users, irrigation water, and hydropower. The results of the study highlight the necessity of implementing sustainable water management strategies, which is timely needed ahead of future anticipated changes in the climate. The temporal shifts of future peak rainfalls should be taken into consideration by the agricultural sector, and awareness should be created among local farmers. The changes in the flow duration curve should also be taken into account for the future development of hydropower. Since there will be increases in rainfall in the nonrainy season in future, water received during this period can be used for agriculture. The authors recommend further studies to be carried out in the region with different GCMs and RCMs and hydrological models. Furthermore, the results of this study highlight the needs of fine-scale RCMs which can replicate the local climate regimes. Proper adaptation options are recommended for this study area for future. This study did not account for changes in land use. However, since these are also expected to change in future, more uncertainties will be included in the future climate change models.

Data Availability

All the data used in this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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Supplementary Materials

Figure A1: ensemble changes in seasonal flows. Figure A2: changes in streamflow. Figure A3: FDCs (a) under RCP4.5 and (b) under 8.5. Table A1: corresponding discharges (in m^3/s) for Q5, Q50, and Q95. (*Supplementary Materials*)

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