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Modeling the future impacts of climate change on water availability in the Karnali River Basin of Nepal Himalaya

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ABSTRACT

It's unequivocal that the global climate is changing, including the rise in atmospheric temperature and variability in amount and pattern of precipitation, and the rate of temperature change in the Himalayan region is higher than the global average. Since precipitation and temperature are the major driving factors of water resources in the Himalayas both upstream and downstream regions, it is important to understand theimpacts of climate change in water resource availability in the future. In this study, we analyzed the historical hydro-climate data and developed a suitable ensemble of the Coordinated Regional Downscaling Experiment (CORDEX) climate models for the Karnali River Basin (KRB) in western Nepal and assessed the future water availability in different climate scenarios using a semi-distributed catchment scale hydrological model the Soil and Water Assessment Tool (SWAT). The climate data analysis shows that the atmospheric temperature is rising throughout the basin but there is high spatial variability in precipitation trend. The historical river discharge data analysis do not show any significant trend, however, there is some inter-annual variability. Future projection shows that the annual precipitation amount will increase compared to the baseline so does the river discharge. However, this increase is not uniform for all seasons. The post-monsoon season having the lowest observed precipitation will get lesser amount of precipitation in the future and the river discharge also follows the same trend. These anomalies play a crucial role in determining the future water availability for agriculture, hydropower, ecosystem functioning and its services availability to the people living in the KRB as well as in the downstream region.

1. Introduction

Himalaya region is water tower for Asia (Immerzeel et al., 2010) and source of several major rivers in Asia, which provide water for about 1.3 billion people inhabiting the mountains and the downstream regions (Bandyopadhyay and Gyawali, 1994; Ives and Messerli, 1989; Xu et al., 2009). These rivers are essential for supplying water for drinking, industries , irrigation, hydropower production, transport and sustaining ecosystems that provide services to the people in downstream (Viviroli et al., 2011). In Nepal, the major river systems originating from the Himalaya have a significant contribution to river discharge even in a dry period because of the snow/glacier melting (Kattelmann, 1987).

The Himalaya region has been identified as one of the most sensitive region in the planet to climate change, and is experiencing the more warming than the global average (Bhutiyani et al., 2007; Kothawale and Rupa Kumar, 2005; Nogués-Bravo et al., 2007; Xu et al., 2009) along with pronounced variability in precipitation (Palazzi et al., 2013), with increasing extreme precipitation events (Goswami et al., 2006; Karki et al., 2017; Sen Roy and Balling, 2004; You et al., 2015; Zhan et al., 2017) and shrinking of glaciers (Bolch et al., 2011, 2012; Kaab et al., 2012; Kehrwald et al., 2008; Yao et al., 2012). These ongoing signs of climate change during the recent decades have significant impacts to glaciers and water resources in the Himalaya region (Cruz et al., 2007; Immerzeel et al., 2009, 2010; Xu et al., 2009), including significant cascading effects on river discharge and groundwater recharge. Few studies in the Himalaya regions show change not only in magnitude in river discharge but also shift in hydrograph due to climate change (Immerzeel et al., 2010; Ragettli et al., 2016; Sharma et al., 2009). Some studies show that climate change is likely to have a greater impact on water supplies annually but more significantly on the seasonal basis (Singh and Bengtsson, 2004, 2005). The subsequent

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changes in river discharge from the Himalaya rivers have profound and long-term impacts on water resources for the livelihoods of people living in this area and the downstream (Akhtar et al., 2008; Carey et al., 2017; Miller et al., 2012; Molden et al., 2016; Nepal et al., 2014). This may pose a potential threat to food and energy security, natural hazard, environmental quality, livelihoods and quality of life of people (Xu et al., 2009).

Water scarcity has already been a major issue in rural watersheds in the middle mountains of Nepal (Merz et al., 2003). Rapid population growth and urbanization accompanied by escalating urban water demands is increasing water transfer from rural and peri-urban areas to urban areas (Shrestha et al., 2015). In addition to this, agricultural water demand is an emerging concern mainly because of agricultural intensification to meet the increasing demand of food to feed growing population (Merz et al., 2003). McDowell et al. (2013) studied the climate-related hydrological change and human vulnerability in mountain regions in Khumbu, Everest region of Nepal and identified reduced water access for household uses, declined crop yields, reduced water access for meeting the high water demands of tourists, and reduced hydro-electricity generation as region-wide impact affecting people.

Projections of global climate models (GCMs) show significant changes in regional and globally averaged precipitation and air temperature in future, and these changes will likely to have associated impacts on water resources (IPCC, 2014). Different climate models indicate that temperature and precipitation are likely to change in the Himalaya region in future with varying magnitudes in different regions. The understanding of climate change in mountains still remains a challenge owing to inadequacies in observations and appropriate models. In order to address these problems, it is important first to understand the present state and then explore the hydrological response in the Himalaya region to climate variability and climate changes in future. In the Himalaya region, the hydrological regime is likely to be affected both by direct impacts on precipitation and evapotranspiration, and indirect impacts through changes in the cryosphere.

As water resources plays a pivotal role for livelihood of people, it is important to understand likely impacts of climate change on future water availability and is very important for water resource management and planning. However, studies on impacts of projected future climate on distributions and availability of water resources are unknown in Karnali River Basin of western Nepal though few researches found the region vulnerable to climate change (Khatiwada et al., 2016; Khatiwada and Pandey, 2019; Pandey et al., 2019b). Therefore, a main objective of this research is to assess the projected impacts of climate change on water availability of Karnali River Basin of the Nepal Himalaya. The specific objectives of the paper are to: (i) Analyze the historical trend of atmospheric temperature, precipitation and river flow in the Karnali River Basin, (ii) Develop the future climate scenario using regional climate model data, and (iii) Assess the future water availability in the basin using projected climate data for the basin. In this study we used Soil and Water Assessment Tool (SWAT) for climate change impact assessment on water availability. Many researcher (Bajracharya et al., 2018; Dahal et al., 2016; Lamichhane and Shakya, 2019; Mishra et al., 2018; Pandey et al., 2019a; Shrestha et al., 2016, 2017) have used SWAT for climate change impact assessment on water availability in different basins of Nepal Himalaya. Dhami et al. (2018) tested the applicability of SWAT in Karnali River Basin and found that model performance was well for hydrological simulation.

2. Study area

The Karnali River Basin (KRB) lies in western Nepal (Fig. 1) between 28.33° -30.45°N and 80.55° -83.68°E and is the largest river basin of Nepal with an area of 42,457 km^2. Karnali River is the trans-boundary river which originates from south of Mansarovar Lake and Mapchachungo Glacier located in China and flows through Nepal joining the Ghaghara River in India. KRB is characterized by high climatic and topographical variability as shown in Fig. 2 (A, C and D). The elevation varies from 163 m in southern lowland to 7747 m at higher mountain to the north. Highland of the KRB is dominated by snow/glaciers and grasslands; and lowland by forest and agriculture lands (Fig. 2 (B)). In the entire basin forest occupies 33 % followed by agriculture land, which occupies 16 %. The KRB is largely rain-fed river basin (Bookhagen and Burbank, 2010). The climate of the KRB is influenced by the monsoon system, physiography of the region, and the westerlies (Nayava, 1980; Shrestha, 2000). The annual average precipitation in the basin is 1479 mm with large spatial, seasonal as well as inter-annual variations (Khatiwada et al., 2016). During the summer monsoon season (June through September), the area receives about 55 %–80 % of the annual precipitation (Shrestha, 2000). Northern part of the basin is the driest part, which receives less than 300 mm precipitation in a year, but there are some pockets in the mountainous areas receiving more than 2400 mm in a year (Fig. 2 (D)) which could be due to orographic relief (Palazzi et al., 2013). The river discharge is dominated by precipitation events in summer in addition to the baseflow coupling with snow and glacier melt in winter.

3. Datasets and methods

3.1. SWAT hydrological model

The Soil and Water Assessment Tool (SWAT) model is a process-based basin scale semi-distributed hydrological model (Arnold et al., 1998) and it is widely used to evaluate the effects of alternative management decisions on water resources. The model is computationally efficient and capable for continuous simulation over long time periods for a varied range of watershed size and environments (Gassman et al., 2007). In SWAT, watershed is divided into multiple sub-watersheds and each sub-watershed is further discretized into hydrological response units (HRUs). Each HRU contains a unique combination of land cover, soil properties and topography. Hydrological balance is simulated in each HRU. These simulations include canopy interception of precipitation, snow and ice melt water, irrigation water, surface and subsurface runoff, distribution of water in different soil profiles, infiltration and groundwater percolation and water flow from shallow aquifer. Detailed theoretical description of SWAT model is provided by Arnold et al. (1998). SWAT model is currently used in about 100 countries to understand complex ecosystem as well as water availability and its quality, climate change impact on water resources and agricultural production issues (Dile et al., 2016) and more than 3000 peer reviewed articles were published using this model by 2017.

3.2. Model input data

A 30 m resolution ASTER Global Digital Elevation Model (ASTER GDEM V2) developed by the Ministry of Economy, Trade, and Industry (METI) of Japan and the National Aeronautics and Space Administration (NASA), USA was used to represent the topography of the basin. The data was downloaded from of NASA Land Processes Distributed Archive Center (http://gdex.cr.usgs.gov/gdex/). The land use map with 30 m spatial resolution derived by object based classification of Landsat thematic mapper imagery (Landsat 5) for the year 2010 was obtained from International Centre for Integrated Mountain Development (ICIMOD) (http://rds.icimod.org/Home/DataDetail?metadataId=9224). Soil map for KRB was obtained from the global soil database prepared by Food and Agricultural Organization of the United Nations (FAO) (http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116). The FAO soil data is available along with a database of soil properties for the top two layers. Soil parameters required for SWAT were calculated from FAO Soil data using the Pedotransfer Function (PTF) developed by Saxton and Rawls (2006). Daily observed precipitation and temperature data were obtained from

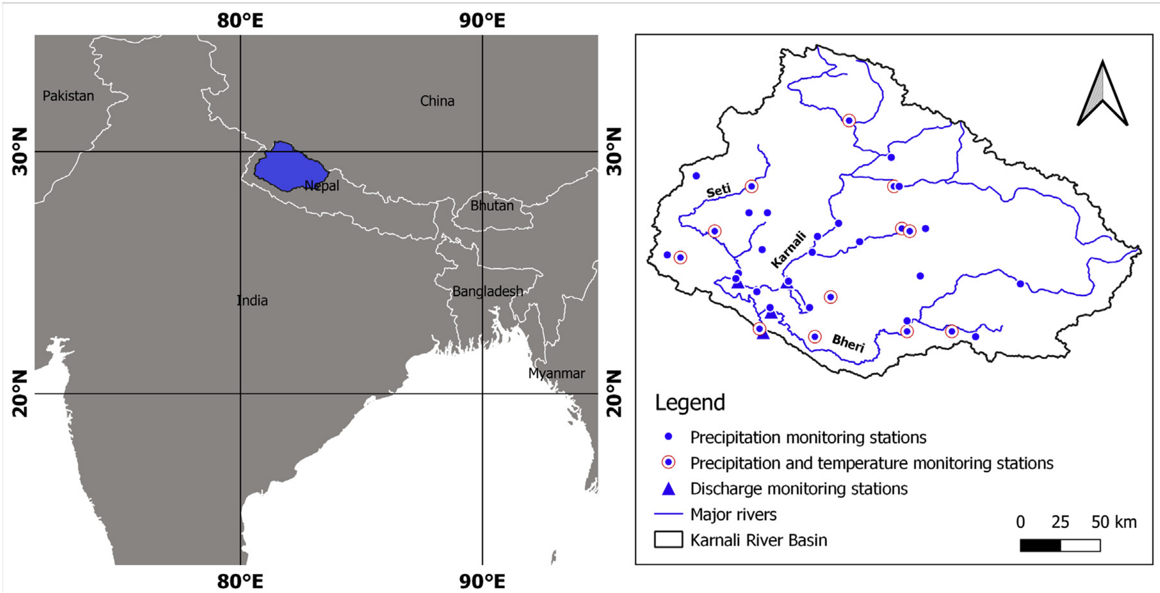

Fig. 1. Location of the study area (shaded blue) in the Nepal Himalaya. Figure in right box shows major rivers and hydro-climatic stations used to construct the model. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

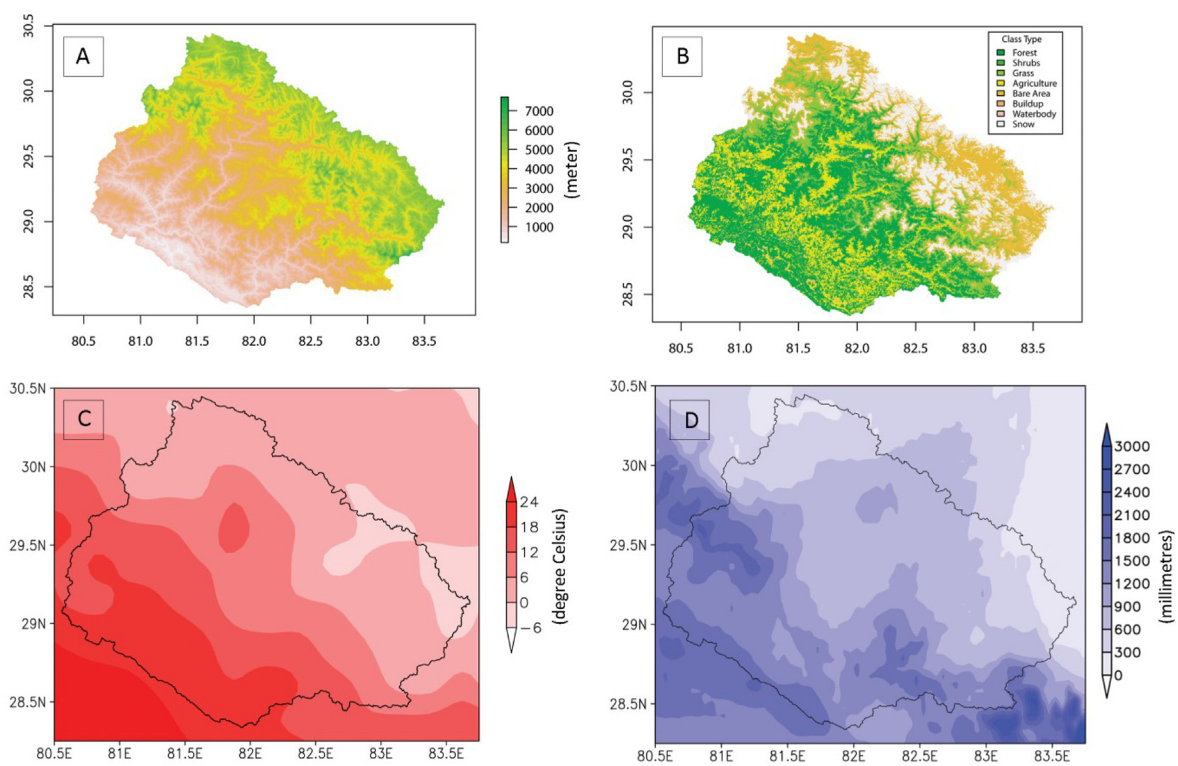

Fig. 2. Spatial variation in (A) altitude in m (Data: NASA et al. (2009)), (B) land cover type (Data: Uddin et al. (2015)), (C) annual temperature in °C (Data: Yasutomi et al. (2011)), and (D) annual precipitation in mm (Data:Yatagai et al. (2012)) in Karnali River Basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the Department of Hydrology and Meteorology (DHM), Government of Nepal. Thirty-four precipitation and twelve temperature stations over KRB were selected for model input data (please refer Fig. 1 for the location of meteorological stations). Daily solar radiation, wind speed and relative humidity data were generated using SWAT inbuilt weather generator functions. A weather generator input file in SWAT contains statistical data needed to generate daily climate data for a sub-basin. For this study, a weather generator input file is prepared using the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) data downloaded from Global Weather Data for SWAT website (https://globalweather.tamu.edu/). Daily average river discharge values for four gauge stations were obtained from DHM (please refer Fig. 1 for the location of river discharge monitoring stations).

Climate model data of 50 km resolution were obtained from Coordinated Regional Climate Downscaling Experiment CORDEX-South Asia (http://cccr.tropmet.res.in/home/ftp_data.jsp) project. In the CORDEX portal, data for six RCMs at the daily time step for different

Table 1
Summary of data and its corresponding resolution and sources.

S.N	Data	Spatial/temporal resolution	Period/Time	Source
A. Physical characteristics of the basin				
1	Digital Elevation Model (ASTER GDEM V2)	30 m	2011	Ministry of Economy, Trade, and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA), USA
2	Land use	30 m	2010	International Center for Integrated Mountain Development
3	Soil	Scale: 1:1,000,000	2007	Food and Agricultural Organization of the United Nations
B. Meteorological/hydrological data				
4	Precipitation, temperature	Point/daily	1981–2005 (Model input) 1981–2016 (Historical trend analysis)	Department of Hydrology and Meteorology, Government of Nepal
5	River discharge	Point/daily	1990–2005 (Model calibration/ validation) 1981–2014 (Historical trend analysis)	Department of Hydrology and Meteorology, Government of Nepal
6	Solar radiation, wind speed and relative humidity	Point/daily	1981–2005	National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR)
C. Regional climate model data for future climate projection				
7	Precipitation, temperature (Ensemble of ICHECRCA4 and CNRMCCAM)	0.05°/daily	1971–2000 (Historical) 2040–2099 (Future)	Coordinated Regional Climate Downscaling Experiment CORDEX-South Asia

time scales and in regular grids for south Asia are available. A few researchers have utilized these data in past in order to assess the reliability and uncertainty in the climate projections for the south Asian region (Ghimire et al., 2015; Mishra et al., 2014). Based on the recommendation from these studies, the dynamically downscaled global climate model data of Irish Centre for High-End Computing (ICHEC) and European Consortium ESM (EC-EARTH)(Hazeleger et al., 2012) by Regional Climate Model of Swedish Meteorological and Hydrological Institute–Rossby Center Regional Atmospheric Model version 4 (CRA4) (Samuelsson et al., 2011) -ICHECRCA4 and global model data of Centre National de Recherches Météorologiques—Groupe d'études de l'Atmosphère Météorologique and Centre Européen de Recherche et de Formation Avancée (CNRM-CM5) (Voldoire et al., 2013) downscaled by CSIRO Marine and Atmospheric Research, Melbourne, Australia -Conformal-Cubic Atmospheric Model (CCAM) (McGregor and Dix, 2008) -CNRMCCAM were selected and an unweight ensemble product of these two models was used to carry out the impact analysis. Future water availability scenarios were developed for two scenarios, RCP 4.5 and RCP 8.5. Summary of data used in this study and its corresponding resolution and sources are presented on Table 1.

3.3. Model setup, calibration and evaluation

On the basis of the DEM, KRB was divided into 25 sub-basins, which were further subdivided into 379 HRUs based on soil, land use, and slope of the land surface. The simulation period was from 1990 to 2005 with a warm-up period for 1981–1989. The warm-up period was used as equilibration to mitigate the initial conditions and excluded from the analysis.

The SUFI-2 algorithm (Abbaspour et al., 2004) in the SWAT-CUP software package was used for model calibration, validation, uncertainty and sensitivity analysis for the SWAT simulation outputs. The best parameters were estimated based on the available data, literature, and subjective judgment. Based on the performance of the model at the basin outlet hydrological station, relevant parameters in the upstream sub-basins were parameterized as suggested by Abbaspour et al. (2015). Based on parameters identified at one-at-a-time sensitivity analysis, initial ranges were assigned to parameters of significance. In addition to the initial ranges, user-defined absolute parameter ranges were also defined for every SWAT parameters in SWAT-CUP where, parameters were not allowed to be outside of this range. Once the model was parameterized and the ranges were assigned, the model was run for 500 iterations.

In calibration and validation, model evaluation was done using statistical model performance evaluation techniques - Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), coefficient of determination (R^2), the percent bias (PBIAS) and ratio of the root mean square error to the standard deviation of measured data (RSR) with a graphical comparison of simulated and measured constituent data. NSE is a normalized statistics which compares of the relative magnitude of the residual variance (noise) and the measured data variance (information) (Nash and Sutcliffe, 1970). R^2 describes the proportion of the variance in the observations explained by the model. The range of R^2 is from 0 to 1 where higher value gives less error variance and values greater than 0.5 are considered as acceptable range (Santhi et al., 2001; Van Liew and Garbrecht, 2003). PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. Positive values of PBIAS indicate model underestimation bias, and negative values indicate model overestimation bias of total volume (Gupta et al., 1999). RSR is the ratio of the root mean square error between simulated and observed values to the standard deviation of the observations (Moriasi et al., 2007). Lower the value of RSR, the better is the model simulation performance. The equations and the interpretation of the values of the statistical model performance evaluation techniques are given in Table 2.

Table 2
Formulae and performance ratings for NSE, PBIAS, RSR and R^2 for calibration and validation processes (adopted from Moriasi et al. (2007) and Moriasi et al. (2015)).

Formulae	Value	Performance Rating
$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(Xobs(i) - Ymodel(i))^2}{\sum_{i=1}^{n}(Xobs(i) - \overline{Xobs})^2}\right]$	> 0.65	Very good
	0.54 to 0.65	Adequate
	> 0.50	Satisfactory
$PBIAS = \left[\frac{\sum_{i=1}^{n}(Xobs(i) - Ymodel(i))}{\sum_{i=1}^{n}(Xobs(i))} \times 100\right]$	< ± 20 %	Good
	± 20 % to ± 40 %	Satisfactory
	> ± 40 %	Unsatisfactory
$RSR = \frac{\sqrt{\sum_{i=1}^{n}(Xobs(i) - Ymodel(i))^2}}{\sqrt{\sum_{i=1}^{n}(Xobs(i) - \overline{Xobs})^2}}$	0.00 < RSR < 0.50	Very good
	0.50 < RSR < 0.60	Good
	0.60 < RSR < 0.70	Satisfactory
	RSR > 0.70	Unsatisfactory
$R^2 = \left[\frac{\sum_{i=1}^{n}(Xobs(i) - \overline{Xobs})(Ymodel(i) - \overline{Ymodel})}{\sqrt{\sum_{i=1}^{n}(Xobs(i) - \overline{Xobs})^2}\sqrt{\sum_{i=1}^{n}(Ymodel(i) - \overline{Ymodel})^2}}\right]^2$	R^2 > 0.50	Satisfactory

Here: Xobs = observed data, $\overline{Xobs}$ = mean of observed data, Ymodel = output data of model simulation, $\overline{Ymodel}$ = mean of output data of model simulation.

3.4. Climate change impact analysis

For this study, the average minimum and maximum temperature and precipitation changes projected by ensemble of two RCMs were calculated for each sub-basin for the period 2040–2069 (mid-century) and 2070–2099 (late-century) for two different emission scenarios – RCP 4.5 and RCP 8.5. Then SWAT simulations were run incorporating these changes on modeled baseline SWAT database for the both periods and scenarios. Mean monthly changes of the basin river discharge and estimated water availability were then compared with the simulated baseline data.

4. Results

4.1. Historical climate trends

KRB does not have a good spatial coverage of meteorological stations to measure the daily climatic parameters especially temperature. Those available are concentrated at lower altitude as shown in Fig. 1. Though there are some stations located in the higher altitude, they have several missing data and/or do not have enough record to analyze their climatic trends (Khatiwada et al., 2016). Therefore, based on the available time scale and data quality, we chose 6 observation stations for temperature trend analysis and 26 stations for precipitation trend analysis. Trends of observed annual temperature (mean, maximum and minimum) and precipitation of each station are presented in Fig. 3 considering the period from 1981 to 2016. The annual temperatures (maximum, minimum and mean) showed an increasing trend except at two stations in case of minimum temperature.

Five stations show statistically significant increasing trend for mean and maximum temperature and three stations in case of minimum temperature. Two stations show decreasing trend of minimum temperature but they are not statistically significant (at alpha = 0.05). The results also show that maximum temperature is increasing at a faster rate than the minimum temperature in KRB (not shown in graphs).

Among 26 precipitation stations, 20 stations show decreasing trend and 7 of them are statistically significant indicating decreasing trend of precipitation in KRB. Among the 6 stations which show an increasing trend of precipitation, 2 of them are statistically significant showing spatial variability in precipitation.

4.2. Projected change in future climate

Fig. 4 presents the spatial changes in temperature over Nepal projected by ensemble of the two RCMs. Results indicate that there is an overall increase in the mean annual temperature across Nepal by the mid-21st century (2040–2069) and and also by the late 21st century (2070–2099) with reference to the baseline period (1971-2000). There is an strong indication that the warming trend is stronger in northern highlands compare to lowlands. Under RCP 4.5 scenario mean temperature could rise by 1.4 °C–2.4 °C during 2040–2069 and 1.6 °C–3.4 °C during 2070–2099. Similarly, under RCP 8.5 scenario the changes in mean temperature could be between 1.8 °C and 3.2 °C during 2040–2069 and 3.4 °C–6.6 °C during 2070–2099.

Fig. 5 presents the future changes in annual total precipitation [%] relative to the baseline period projected by ensemble of the two RCMs. Results indicate that more precipitation is expected in most of the areas for both scenarios (RCP 4.5 and RCP 8.5) and time scales (mid and late-century) except in some part of eastern and central Nepal. In KRB, where a decreasing trend in precipitation is observed in the recent decades, the models project an increase in precipitation even in mid of the 21st century. Unlike that of temperature, precipitation trends are not uniform. Results show that under RCP 4.5 scenario the total annual precipitation may increase by 12 %, but under RCP 8.5 scenario it may increase by 30 %.

The monthly variability in the observed and future precipitation in KRB (Fig. 6) shows that pre-monsoon and monsoon precipitation is expected to increase during the 2040–2069 and the 2070–2099 compared to the baseline period. Contrast to this, both RCP 4.5 and RCP 8.5 scenarios show decreasing precipitation in November for both time scales, which is the driest month for the basin. This could lead to increase in winter droughts in KRB in future.

4.3. Historical trend of river discharge

The location of the hydrological stations measuring discharge along with three major tributaries in KRB: Bheri at east, Seti at west and Karnali at the center are shown in Fig. 1. The observed river discharge data do not show any statistically significant trend at 95 % confidence level, but they have a large inter-annual variability (Fig. 7). The mean annual discharge at the Chisapani station at the outlet of KRB is 1375 m^3s^{-1}.

4.4. Model calibration and validation

The SWAT hydrological model for KRB was calibrated and validated against the monthly observed discharge data at the basin outlet at Chisapani. Model calibration and validation were carried out by comparing simulated and measured data for the period 1990–1997 and 1998–2005 respectively. Sequential Uncertainty Fitting II (SUFI-2) (Abbaspour et al., 2004) method using SWAT-CUP (Calibration and Uncertainty Program) (Abbaspour et al., 2007) was first used, with the

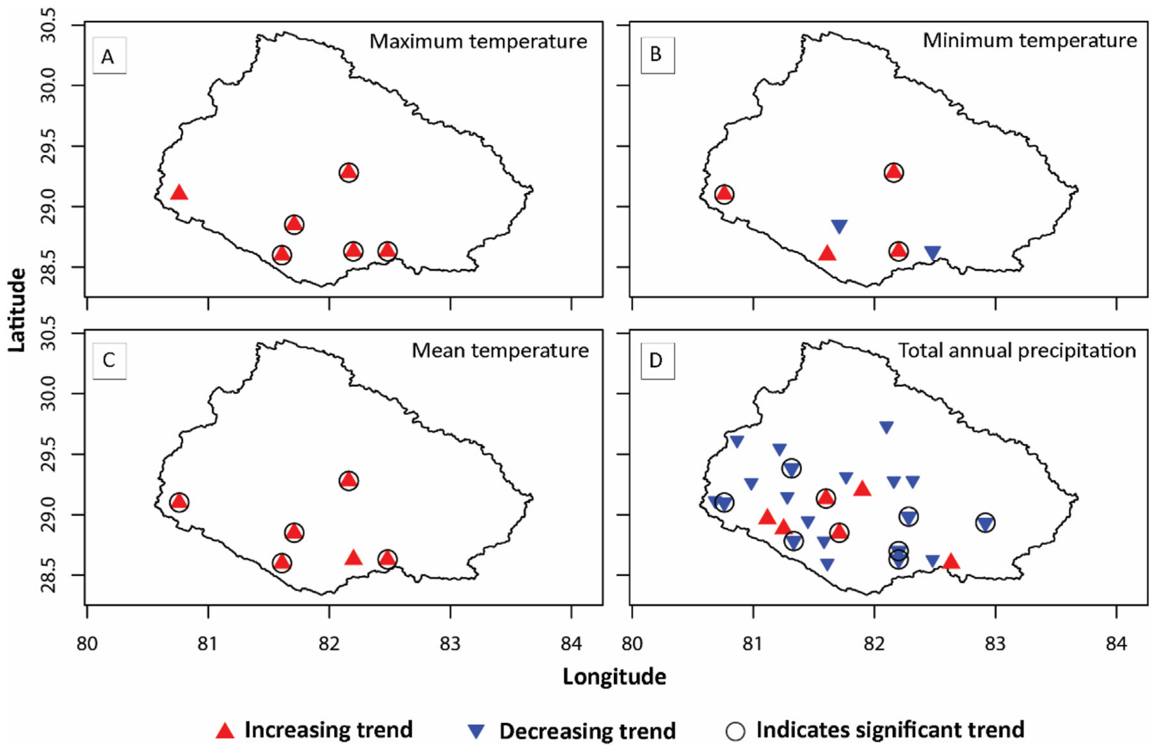

Fig. 3. Trend of observed (A) maximum temperature (B) minimum temperature (C) mean temperature and (D) total annual precipitation of each station in Karnali River Basin (1981–2016).

NSE as the objective function, to identify the most sensitive parameters to be calibrated in KRB. After choosing the sensitive parameters, feasible range of these parameters were estimated based on the available data, literature, and researchers' expertise and then simulations were carried out.

The graphical comparison between the observed and simulated monthly discharge for both calibration and validation periods show that basin exhibits good agreement between the simulated and observed

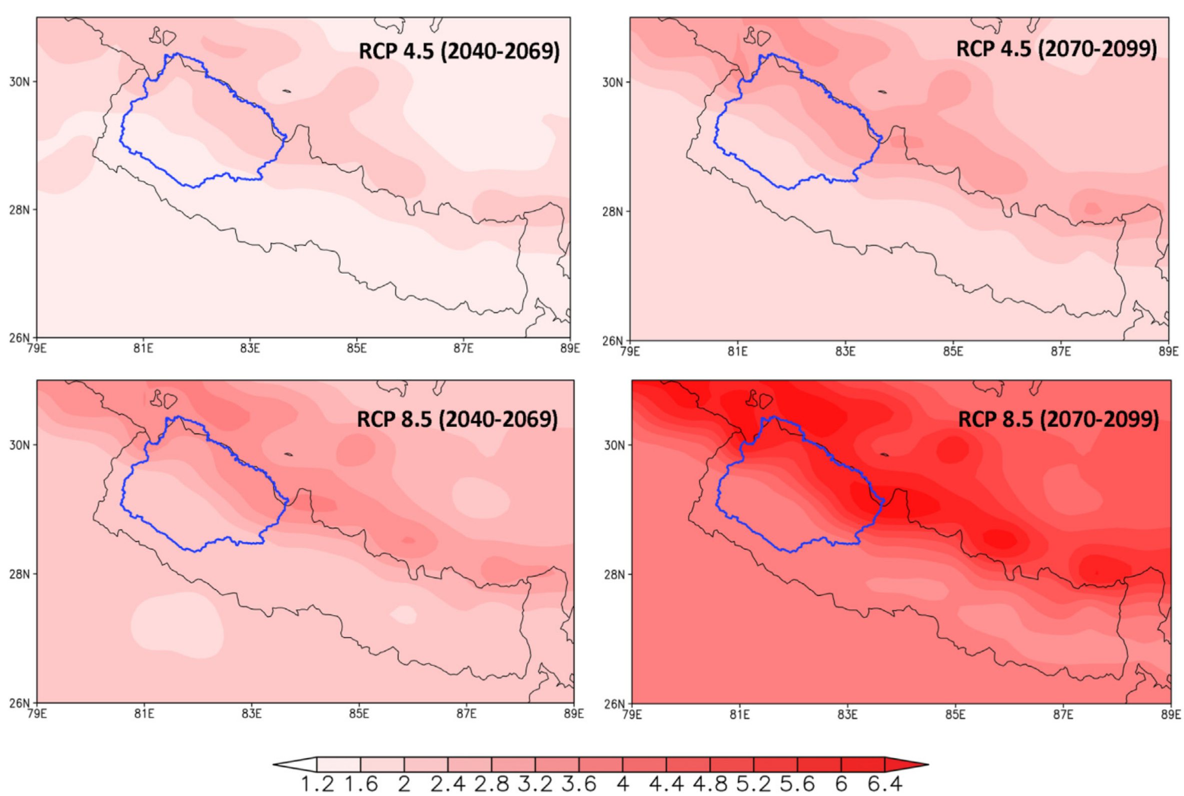

Fig. 4. Projected change in the future mean annual temperature [°C] by ensemble of the two RCMs over Nepal for two different scenarios (RCP 4.5 and RCP 8.5) and time scales (2040–2069 and 2070–2099) relative to the baseline period of 1971–2000.

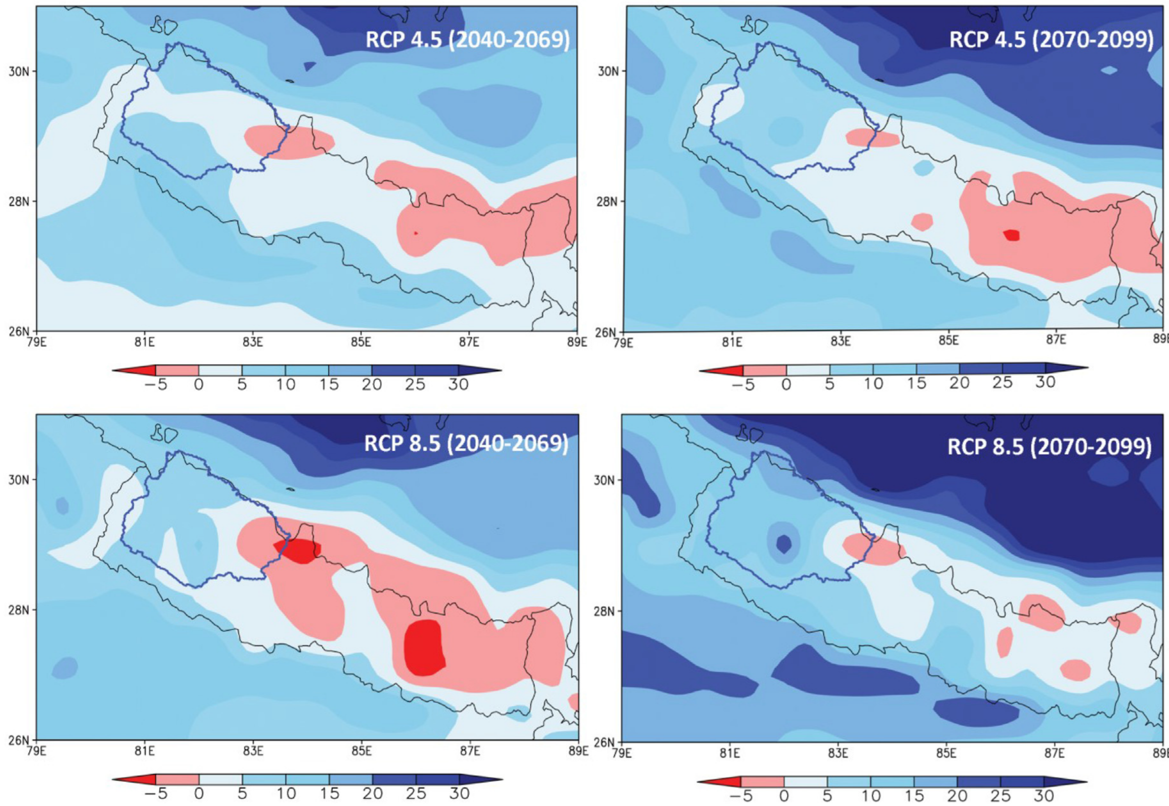

Fig. 5. Projected changes in the future annual total precipitation [%] by ensemble of the two RCMs over Nepal for two different scenarios (RCP 4.5 and RCP 8.5) and time scales (2040–2069 and 2070–2099) relative to the baseline period of 1971–2000.

discharge (Fig. 8). The NSE values during the calibration and validation periods were 0.85 and 0.83 respectively. Similarly, the cumulative volume of the simulations exceeded that of the observations by 1.9 % during the calibration period and by 3.9 % during the validation period indicating a slight overestimation of the discharge by the model during the simulation period.

The statistics of the model performance is summarized in Table 3. On the basis of recommendations provided by Moriasi et al. (2007), model performance as assessed by NSE, R^2, PBIAS and RSR was 'very good'. This shows that model performed good in simulating river discharge and was capable of capturing monthly variation of discharge for KRB.

4.5. Impacts of climate change on river discharge

Baseline and future projection of monthly river discharge at the outlet location of the Karnali River Basin as simulated by SWAT are presented in Fig. 9. The increase in precipitation has been reflected in the discharge. It shows an overall increase in discharge for both the mid (2040–2069) - and late (2070–2099) -century compared to the baseline period (1971–2000). Results show that annual mean discharge will increase by 6.4 % during 2040–2069 and 8.4 % during 2070–2099 under RCP 4.5 scenario whereas 5.1 % in 2040–2069 and 10.9 % in 2070–2099 under RCP 8.5 scenario. The rate of increment of discharge is higher in pre-monsoon (March–May) and monsoon

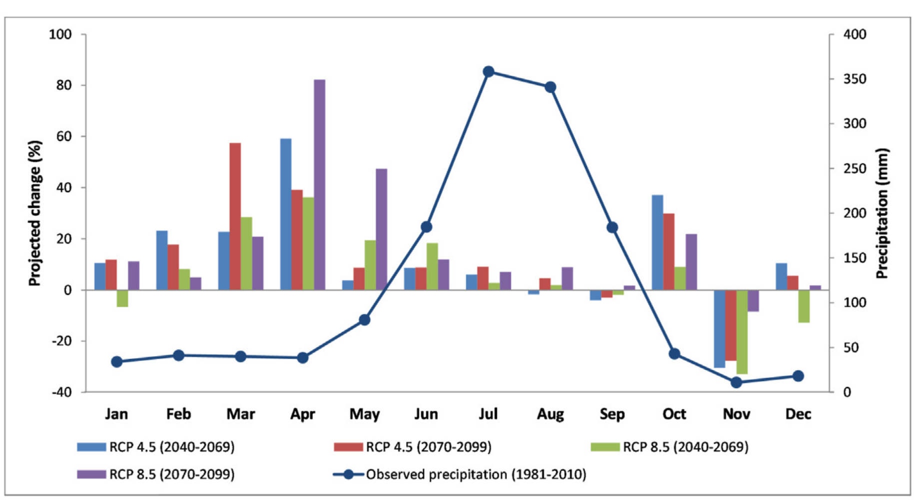

Fig. 6. Monthly variation of observed precipitation and projected changes [%] in Karnali River Basin for different scenarios and time scales. Future projection is relative to the baseline period of 1971–2000.

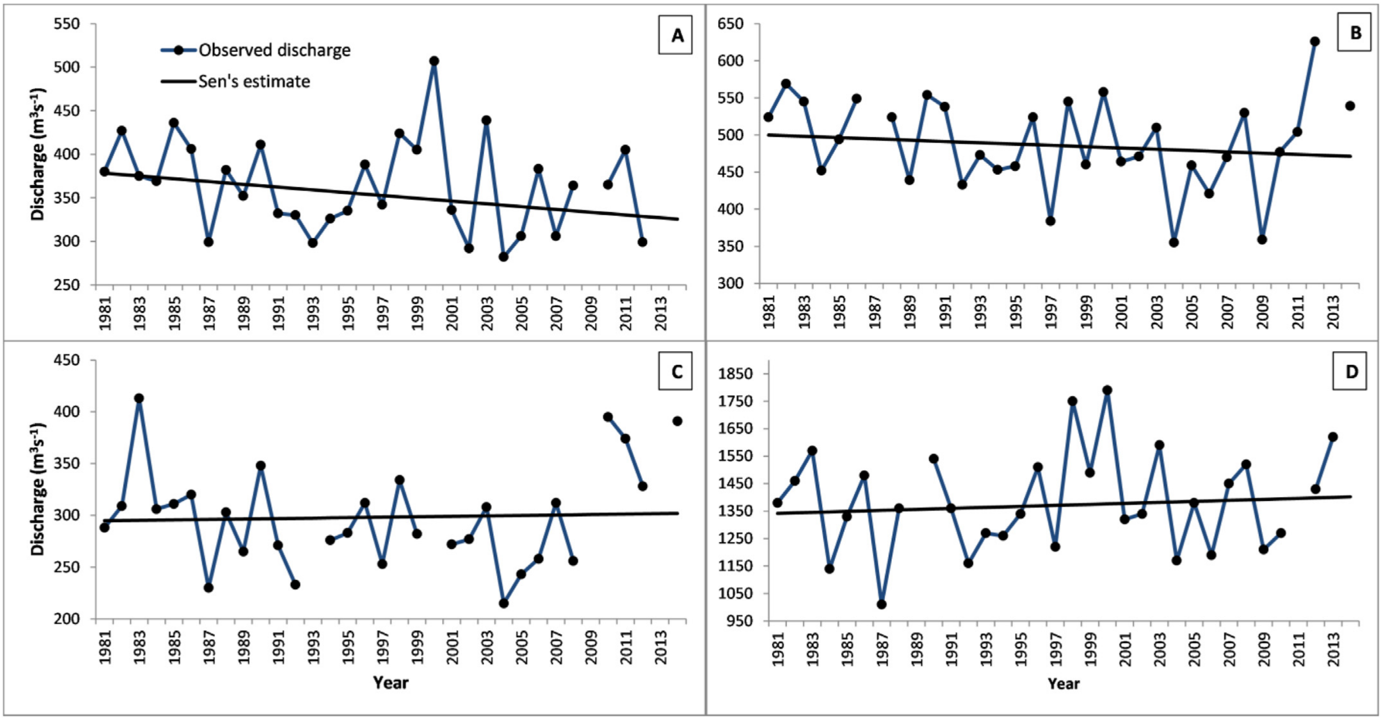

Fig. 7. Variability on observed annual average river discharge in (A) Bheri River (at Jamu: station index-270), (B) Karnali River (at Asharaghat: station index-240), (C) Seti River (at Banga: station index-260), and (D) outlet of the Karnali River Basin (Karnali River at Chisapani: station index-280).

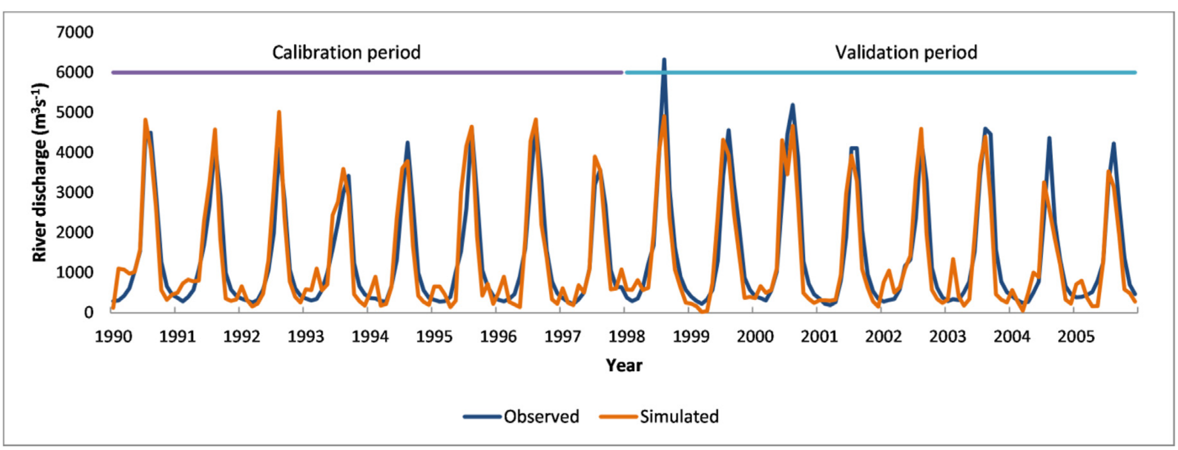

Fig. 8. Comparison between observed and simulated monthly discharge for both calibration and validation periods at the outlet of the Karnali River Basin (Karnali River at Chisapani).

Table 3
Summary statistics of model performance.

Criteria for model skill evaluation	Calibration	Validation
Nash-Sutcliffe Efficiency (NSE)	0.85	0.83
Percent Bias in Volume (PBIAS)	1.90	3.90
Coefficient of Determination (R^2)	0.86	0.84
RMSE-observations Standard Deviation Ratio (RSR)	0.39	0.41

(June–September) seasons. RCP 8.5 for mid-century projected to decrease discharge during the early winter causing dry winter. The percentage changes in discharge for each season projected by different scenarios are presented in Fig. 10.

5. Discussion

Through this analysis, we show that KRB's climate has clearly warmed since 1981. This result is coherent with the studies in other parts of the Nepal Himalaya (Baidya et al., 2008; Nepal, 2016; Sharma et al., 2000; Shrestha and Aryal, 2011; Shrestha et al., 1999). Many researchers claimed that there is relatively higher warming trends in higher altitude compare to lowland in Himalaya and other regions (Bhutiyani et al., 2007; Hu et al., 2012; Immerzeel, 2008; Liu et al., 2009; Pepin et al., 2015; Qin et al., 2009; Rangwala and Miller, 2012; Shrestha and Aryal, 2011).

Another result shows the decreasing trend of precipitation in KRB since 1981 in a regional scale but there is geographic and interannual variability in precipitation in the region. Unlike to all agreed increasing trend of temperature in the Himalaya region, similar other studies on precipitation trend in the adjacent area show mixed spatial results. Shrestha et al. (2000) did not find any significant trend in precipitation in the Nepal Himalaya. In Koshi River Basin, Nepal (2016) studied the trend of precipitation of 36 stations and found 22 stations showing increasing trend while only 2 stations were statistically significant.

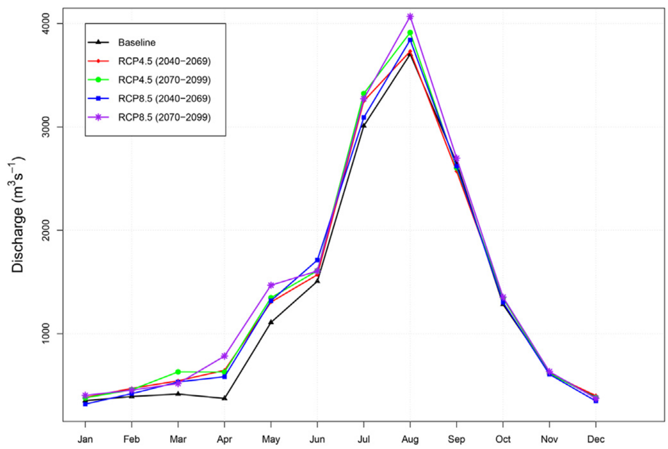

Fig. 9. Future projected monthly flows in Karnali River Basin.

Among them 14 stations showed a decreasing trend of which only 1 station showed significant trend. These results indicate that the climate of the KRB has become warmer and drier during the last 36 years.

The increasing trend of temperature in future is supported by many previous studies using different global climate models (GCMs) and regional climate models (RCMs), and different emission scenarios. Lutz et al. (2014) studied projected temperature change for the Asia's five major river basins - Indus, Ganges, Brahmaputra, Salween and Mekong. They found that GCMs agree on, between the reference period (1998–2007) and 2050, temperatures will increase in the region from ~1 °C to 2.2 °C. Palazzoli et al. (2015) studied future climate scenarios in Indrawati Basin in Nepal using three climate models (GCMs), namely, CCSM4, EC-Earth and ECHAM6, each one under three different RCPs (2.6, 4.5 and 8.5) and found that temperature increase is expected in all the scenarios, and the greatest increase is expected under RCP 8.5. Zomer et al. (2014) studied projected climate change based upon an ensemble of 19 Earth System Models (CIMP5) across four RCPs within the Kailash Sacred Landscape of China, India and Nepal and found that the mean annual temperature would increases by 2.2 °C (RCP 2.6) to 3.3 °C (RCP 8.5) in the mid-21st century compare to the mean temperature of 1960–2000. Dahal et al. (2016) studied the projected climate change in Bagmati River Basin in Nepal using CORDEX SMHI-RCA4 model data and found that temperature is likely to increase in future under both RCP 4.5 and RCP 8.5 and the magnitude will be larger under RCP 8.5. Rajbhandari et al. (2016) studied the projected change in temperature in Koshi River Basin using eight CMIP5 GCMs data and found that higher increase in temperature is projected to be over the high Himalaya and middle mountain area compared to trans-Himalaya and southern plain areas. Though the basin is likely to experience warming throughout a year, the increase rate in winter is likely to be higher compared to other seasons. Pandey et al. (2019a) studied projected change in temperature in Chamelia watershed of Mahakali Basin using ensemble of five RCMs and found increasing trend to the end of the century for both maximum and minimum temperatures. This pronounced warming in future would inevitably enhance evapotranspiration, change in snow cover dynamics, which cause rapid melting of glaciers with increasing risk of 'too much water and too little water' for people.

The precipitation does not show uniform trend in the past observation and also in the future projections. Expected changes in precipitation in this region are not consistent in all the regions although many studies predicted slightly increased precipitation (Dahal et al., 2016; Dhaubanjar et al., 2019; Lutz et al., 2013, 2014; Palazzi et al., 2013; Pandey et al., 2019a; Shrestha et al., 2016) with an increase in summer and decrease in winter seasons (Rajbhandari et al., 2016). In Koshi River Basin Rajbhandari et al. (2016) found that, in future by 2050, precipitation is likely to increase by 14 % during the summer monsoon season and the increase is higher over the mountains than the plains. The meager amount of precipitation in the winter season is also projected to further decrease.

Though there is clear trend of warming and decreasing precipitation, there is absence of trend in river discharge in KRB. Bur river discharge shows large inter annual variability. Gautam and Acharya (2012) studied statistical trend of river discharge over Nepal using Mann-Kendall and Sen's test and found that a majority (~66 %) of the hydrological stations mostly draining the larger basin showed an absence of any significant trends. Gurung et al. (2017) studied long term river discharge trend in four trans-boundary basins across the Himalaya range including Koshi and Gandaki rivers of Nepal Himalaya and found that none of the trends was statistically significant. In KRB precipitation in the high-elevation areas falls as snow, causing a natural delay in the river discharge therefore snow-cover dynamics in the upstream also influence the water availability in the downstream. The runoff contributions from the snow/ice and glacier respond to variations in climatic conditions in different ways (Cayan et al., 1993; Duell, 1994;

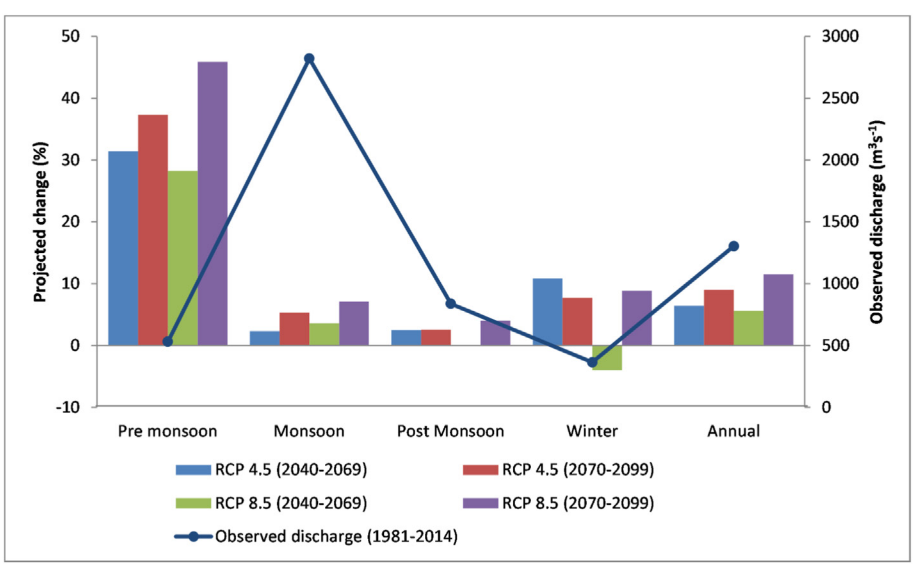

Fig. 10. Change in discharge at outlet of Karnali River Basin for each season projected by different scenarios. Blue line is the observed seasonal mean discharge (m^{3}s^{-1}). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Kletti and Stefan, 1997). On an annual timescale, snowmelt provides 20.5 % of discharge in KRB (Bookhagen and Burbank, 2010). Here, the contrasting result of decreasing precipitation and non-significant trend in river discharge may be confounded by the climate warming–driven changes in snowpack, permafrost, glacier, and evapotranspiration. Increasing melt rate may be compensating the decreasing precipitation.

Hydrological models driven by climate simulations predict an overall increase of river discharge over KRB. This result is clearly sensitive to result of future climate projections. Immerzeel et al. (2012) stated that the increasing river discharge in future mostly contributed by increases in precipitation and temperature in Langtang River Basin of Nepal Himalaya. Such a significant increase was also reported by Shrestha et al. (2016), Mishra et al. (2018), Dahal et al. (2016), Lamichhane and Shakya (2019), Bajracharya et al. (2018), Shrestha et al. (2017), Pandey et al. (2019a) in different other river basins of Nepal Himalaya. Pandey et al. (2019a) used similar approach to study hydrological response to climate change in Chamelia watershed of Mahakali Basin, adjacent to KRB, and found that average annual discharge was simulated to increase by 8.2 % in 2021–2045, 12.2 % in 2046–2070, and 15.0 % in 2071–2095 under RCP 4.5 scenario.

Though, KRB is the region having least hydropower projects in Nepal to date, it has highest potential of hydroelectricity generation among river basins in Nepal (Sharma and Awal, 2013) and significant number of hydroelectric projects are under construction and many are in the pipeline in this region (Alam et al., 2017). As most of Nepal's existing and proposed hydropower plants are run-of-river schemes, the amount of electricity generated is highly dependent on the daily discharge. Therefore knowledge regarding future water availability in Karnali River Basin is very much relevant since hydropower is envision as one of the important sector for development of region (Pakhtigian et al., 2019).

6. Conclusion

In this study future water availability in the Karnali River Basin of the Nepal Himalaya was analyzed by developing the SWAT hydrological model. The model performed good in simulating river discharge and is capable of capturing monthly variation of the discharge for the model calibration and validation periods with NSE values 0.85 and 0.83 respectively. The results show that the mean temperature in the basin is projected to increase by 1.4 °C to 2.4 °C for 2040–2069 and by 1.6 °C to 3.4 °C for 2070–2099 under RCP 4.5 scenario and by 1.8 °C to 3.2 °C for 2040–2069 and by 3.4 °C to 6.6 °C for 2070–2099 under RCP 8.5 from the baseline period of 1971–2000. This increasing trend in mean temperature is similar to the past trend. In the case of precipitation, overall it is projected to increase in annual total but more likely to increase in pre-monsoon and monsoon seasons. Results show that, under RCP 4.5 the annual total precipitation may increase by 12 %, and under RCP 8.5 it may increase by 30 % compared to the baseline period 1971–2000. Analyses conclude that rising temperature and change in precipitation patterns across the Karnali River Basin resulting from climate change will have an influence on water resource availability in future. The annual average discharge of the river will increase by 6.4 % by 2040–2069 and 8.4 % by 2070–2099 under RCP 4.5 and 5.1 % by 2040–2069 and 10.9 % by 2070–2099 under RCP 8.5. More water will be available especially during the pre-monsoon and monsoon seasons, and this scenario is likely to increase in the late century. It may be with a caveat of increased potential of floods and extreme events, which would be more harmful in the low-lands, especially during the monsoon season. Riverine, and urban floods linked to extreme precipitation events could cause widespread damage to infrastructure, livelihoods and settlements in future.

CRediT authorship contribution statement

Piyush Dahal: Methodology, Formal analysis, Writing - original draft. **Madan Lall Shrestha:** Writing - review & editing. **Jeeban Panthi:** Methodology, Writing - review & editing. **Dhiraj Pradhananga:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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