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ORIGINAL ARTICLE

Modelling the potential impacts of climate change on hydrology and water resources in the Indrawati River Basin, Nepal

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Abstract The Government of Nepal is planning to divert water from the Indrawati River Basin into the Kathmandu Valley to curb the decade-long water scarcity problem. However, climate change might alter water availability in the basin, hence affecting future water diversion strategies. Therefore, this study examines the potential impact of climate change on hydrology and water availability in the Indrawati River Basin of Nepal. The climate change scenarios from one regional climate model namely, HadGEM3-RA and two general circulation models namely, MIROC-ESM and MRI-CGCM3, each one under two different representative concentration pathways (RCPs), were fed into the Soil and Water Assessment Tool (SWAT) and hydrological changes were estimated for eight time frames: 2020s, 2030s, 2040s, 2050s, 2060s, 2070s, 2080s, and 2090s against the baseline period (1995–2004). The results show that the temperature in the basin could increase by 2.5–4.9 °C by the end of the century. The average annual precipitation in the basin is projected to increase in the future but the magnitude varies with time and the RCP scenarios. Similarly, the study shows an increase in annual discharge in both the Melamchi and Indrawati Rivers, but the monthly analysis reveals that the changes are not uniform. The discharge in the Melamchi River is projected to decrease during March–July and increase during August–February. In the Indrawati River the discharge is projected to decrease during November–April and increase during May–October. The findings show that the discharge into the Melamchi River during March and April will be sufficient for diverting water into the Kathmandu Valley. The results of this study will be useful for preparing an adaptation plan to offset the negative impacts, while at the same time harnessing the positive impacts of climate change in the basin.

Keywords Indrawati Basin · Climate change · RCP scenarios · SWAT

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Introduction

We live in an era of rapid global climate change and almost all scientists have utmost confidence that human beings are solely responsible for such change. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicates that there is growing confidence that some extremes will become more frequent, widespread and/or more intense during the twenty-first century (IPCC 2007). Countries in Asia have been experiencing more frequent floods and droughts over the past decades as a consequence of climate change and human activities (Xu et al. 2013).

Although climate change is a global phenomenon, its impact mostly occurs at regional level (Xu et al. 2013). Climate change is expected to alter temperature and precipitation patterns and it may therefore affect river discharge, seasonal and local water availability, and water supply (Olmstead 2013; Aristeidis et al. 2012; Arnell 2003). Therefore, it is very important to investigate the impact of climate change on hydrology at a regional level or basin scale (Teutschbein and Seibert 2012; Babel et al. 2013; Xu et al. 2013; Olmstead 2013).

The assessment of climate change impact on hydrology is a challenging task due to the various uncertainties

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involved such as streaming from the greenhouse effect, and the structure and parameters of GCMs (Xu et al. 2013). The construction of ensemble projection in climate change is one of the methods used to address uncertainty issues in climate change related studies. There are different ways to prepare an ensemble projection of GCMs, and arithmetic ensemble is one of the simplest ways (Lambert and Boer 2001). Hence, multiple climate models are used in this study to address the uncertainty and provide more quality information on climate change impact studies (Minville et al. 2008; Xu et al. 2013; Nkomozepi and Chung 2014).

Most climate change impact studies conducted in the past are based on the Special Report on Emissions Scenarios (SRES) of IPCC Assessment Report 4 (AR4). For this study new climate scenarios, RCPs, proposed by IPCC Assessment Report 5 (AR5) are used. The RCP scenarios include the highest and lowest emissions of greenhouse gases (GHGs) examined by the climate modelling community which includes mitigation measures that may be applicable in the future to control the emission of GHGs. This feature was not seen in SRES. The lowest emission scenario in RCPs is consistent with the aim of stabilising the mean temperature to less than 2 °C. The RCPs also focus on emissions relevant for short-lived climate forces such as sulphate aerosols (van Vuuren et al. 2011).

In Asia, the average temperature is expected to rise by 1.8–3.9 °C and precipitation is projected to increase by 1–12 % by the end of the century (IPCC 2007). Climate change studies conducted in Nepal suggest that the temperature is likely to increase continuously throughout the twenty-first century (Mishra and Herath 2010; Babel et al. 2013; Shrestha et al. 2014). With increasing temperatures, precipitation, and the melting of snow, the probability of an increase in river discharge and flooding is expected during the wet season. On the other hand, droughts may occur during the dry season.

The Kathmandu Valley currently faces a huge scarcity of drinking water. With a total population of about 2.51 million (CBS 2011), the water demand of the valley is 350 million litres per day (MLD) (equivalent to 0.35 MCM/day) (KUKL 2011). The Kathmandu Upatyaka Khanepani Limited (KUKL), the main authority for supply water in the valley, is only supplying water at an average of 0.07 MCM/day in the dry season and 0.12 MCM/day in the wet season (KUKL 2011). To deal with the increasing water scarcity in Kathmandu Valley, the Government of Nepal (GoN) launched the Melamchi Water Supply Project (MWSP) in 1998. The MWSP is an inter-basin water diversion project, designed to transfer 510 MLD (equivalent to 0.51 MCM/day) from Melamchi, Yangri, and Larke Rivers of the Indrawati River Basin (IRB). The project is divided into three stages of water diversion: Stage I: 0.17 MCM/day from the Melamchi River; Stage II: 0.17 MCM/day from the Yangri River; and Stage III: 0.17 MCM/day from the Larke River (MWSDB 1998). The water from each river will be diverted into the Kathmandu Valley through a 26.5 km long tunnel to a treatment plant at Sundarijal, Kathmandu. Water after treatment will be distributed by a bulk distribution system to 15 reservoirs located around the Kathmandu Valley. The project was implemented in 1998 with a loan from the Asian Development Bank (ADB), and was scheduled for completion by 2008. However, due to various problems, the project is still in the early construction phase. With the delay in construction and a rapid population growth rate, the situation of water shortage is likely to get even worse. Although climate change may affect the viability of the project, analysis of its impact was ignored during the formulation of this large-scale project.

It seems apparent that very few research studies have been conducted in the IRB regarding climate change impact assessment, and furthermore no research has yet been conducted using the new RCP scenarios. Therefore, the main objective of the study is to project future climate scenarios and assess the impact of climate change on the hydrology of the Melamchi and Indrawati Rivers in the IRB of Nepal.

Data and methods

Study area description

The IRB is an important river basin due to its significance in water diversion into the Kathmandu Valley. The IRB is situated in the mid-hills of Nepal and has a high variation in altitude. The altitude ranges from 595 to 5838 m above sea level (masl). Over a short distance, the area comprises snow-covered mountains and a plain area. The basin is approximately 50 km north east from the capital city of Nepal in Kathmandu (Fig. 1). The basin lies within the latitude 27°27′11″ N–28°10′12″ and longitude 85°45′21″E–85°26′36″E with a total drainage area of 1230 km^2. The main tributaries of the Indrawati River are Melamchi, Yangri, Larke, Mahadev, Chaa, Handi, and Jhyangri. Among all the tributaries, water from the Melamchi, Yangri, and Larke Rivers is planned for diversion into the Kathmandu Valley.

The climate of the IRB varies from alpine in the higher mountains to sub-tropical in the southern lowlands. The climate of the IRB can be divided into three precipitation seasons: pre-monsoon (January–May), monsoon (June–September), and post-monsoon (October–December). The average annual rainfall varies from 1200 to 3000 mm with about 80 % occurring during the monsoon season. The average temperature of the basin ranges from 4 to 33 °C and the mean relative humidity is in the range of 60–90 %.

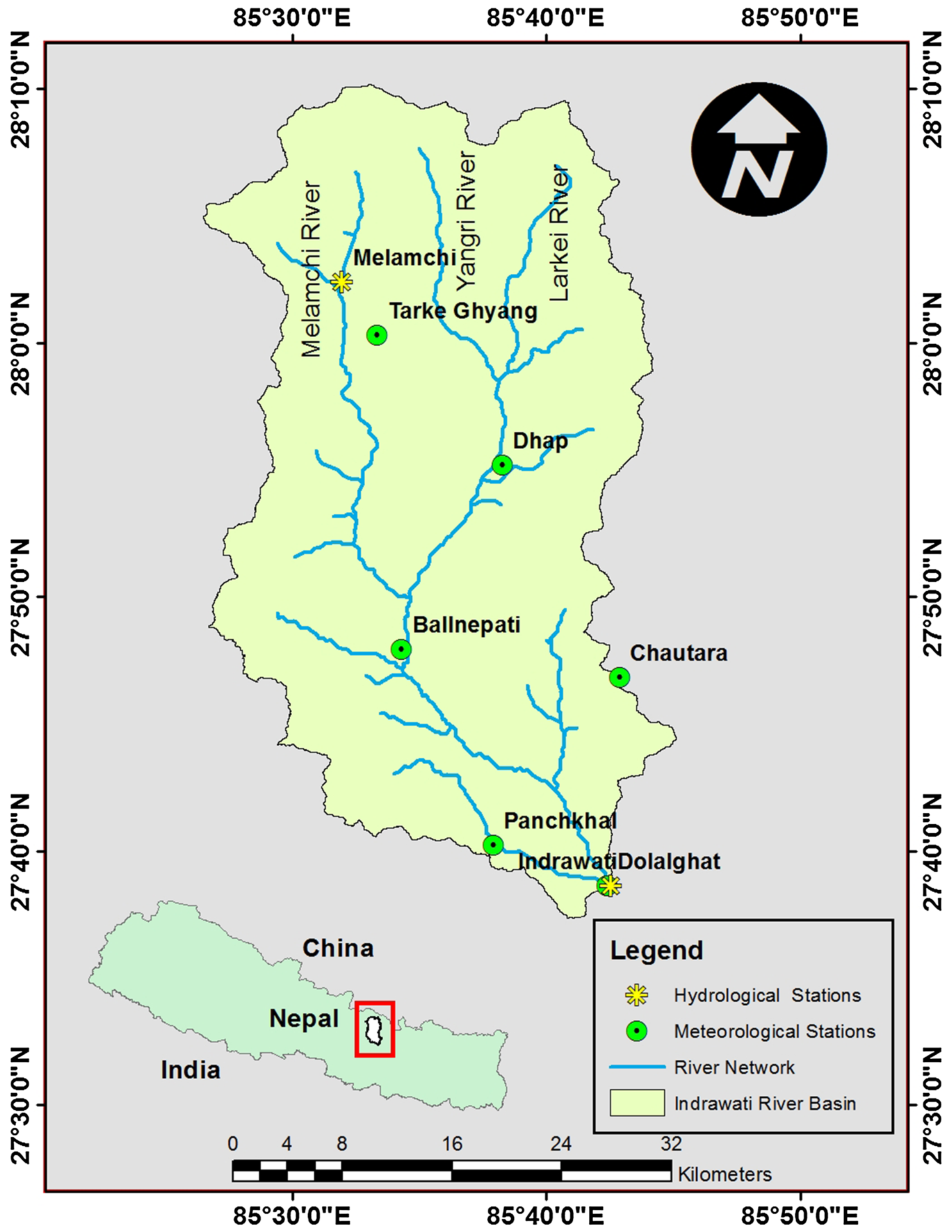

Fig. 1 Location map of the study area showing the river network and hydro-met stations in Nepal

There are two discharge gauging stations in the IRB: one in the Melamchi River at Helambu and the other at the basin outlet of the Indrawati River at Dolalghat. The annual average discharge in the Melamchi and Indrawati Rivers is 10.21 and 75.06 m^3/s, respectively.

Methodology

Future climate scenarios

This study mainly focuses on future climate projection and the examination of its effect on the hydrology of the IRB. One RCM: HadGEM3-RA and two GCMs: MIROC-ESM and MRI-CGCM3 are used to project future precipitation, together with the maximum and minimum temperatures of the basin. This study uses two RCP scenarios: RCP 4.5 and RCP 8.5, which represent future medium and high emissions of carbon. The linear scaling method of bias correction was applied to the grid-based climate model data for local observed stations to predict the future climate in a decadal time frame.

The RCPs are four greenhouse gas concentration trajectories adopted by the IPCC for its Fifth Assessment Report (AR5) in 2014 (Table 1). For this study, future time periods are divided into a decadal time frame as follows: 2020s (2021–2030), 2030s (2031–2040), 2040s (2041–2050), 2050s (2051–2060), 2060s (2061–2070), 2070s (2071–2080), 2080s (2081–2090), and 2090s

Table 1 Overview of representative concentration pathways (RCP) scenarios

RCP	Description	Temp. anomaly (°C)	CO_2 concentration (ppm)
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100	4.9	1370
RCP 6.0	Stabilisation without overshoot pathway to 6 W/m^2 at stabilising after 2100	3.0	850
RCP 4.5	Stabilisation without overshoot pathway to 4.5 W/m^2 at stabilisation before 2100	2.4	650
RCP 2.6	Peak in radiative forcing at 3 W/m^2 before 2100 and reaching 2.6 W/m^2 by 2100	1.5	490 then declines

Source: (van Vuuren et al. 2011)

Table 2 Climate models used to project climate change scenarios in the study basin

Climate model	Resolution	Future data period	Sources
HadGEM3-RA	0.44° × 0.44°	2006–2100	http://cordex-ea.climate.go.kr
MIROC-ESM	2.79° × 2.8125°	2006–2100	http://pcmdi9.llnl.gov/
MRI-CGCM3	1.875° × 1.875°	2006–2100	http://pcmdi9.llnl.gov/

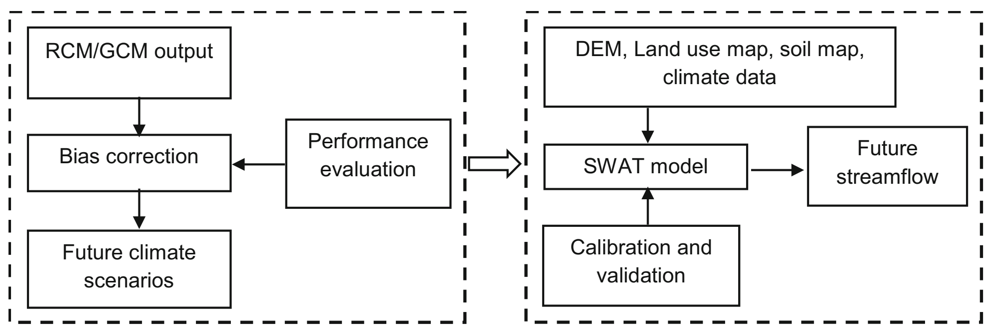

Fig. 2 Research methodology framework used in this study

(2091–2100). The outputs from the RCM and GCMs were used to project climate scenarios up to the year 2100 in a decadal time frame (Table 2). The RCM and GCMs were selected based on two criteria: (a) data availability; and (b) representativeness of model to the observed stations. The monthly average precipitation and temperature of RCM/GCMs were compared with the monthly average measured data. Statistical parameters such as R^2, root mean square error (RMSE), mean and standard deviation of observed data and model were compared before and after bias correction to check the suitability of climate models (Fig. 2).

Downscaling climate variables

The RCMs/GCMs give good results in mimicking the observed data on a large scale. However, they still have some bias which needs to be corrected while studying at basin level. The linear scaling factor method (Ines and Hansen 2006; Teutschbein and Seibert 2012) is used to correct the biases of the RCM and GCMs for this study. This method is based on the difference between monthly observed and simulated values. These differences are then applied to simulated climate data to obtain bias corrected climate variables. Additive correction is preferable for temperature, whereas multiplicative correction is more appropriate for variables such as precipitation, vapour pressure, solar radiation etc. Additive correction ensures that absolute changes in temperature are not modified but the reference starting level is adjusted to the observed level. However, for precipitation and other non-negative parameters such as vapour pressure and solar radiation, the multiplicative approach is chosen to ensure non-negative bias corrected data (Hempel et al. 2013).

The equations below are used for the linear scaling factor method:

$$P_{his}(d)* = P_{his}(d) \times [\mu_m(P_{obs}(d))/\mu_m(P_{his}(d))] \quad (1)$$

$$P_{sim}(d)* = P_{sim}(d) \times [\mu_m(P_{obs}(d))/\mu_m(P_{his}(d))] \quad (2)$$

$$T_{his}(d)* = T_{his}(d) + [\mu_m(T_{obs}(d)) - \mu_m(T_{his}(d))] \quad (3)$$

$$T_{sim}(d)* = T_{sim}(d) + [\mu_m(T_{obs}(d)) - \mu_m(T_{his}(d))] \quad (4)$$

where, d = daily, μ_m = long term monthly mean, * = bias corrected, his = RCM/GCM simulated 1981–2005, sim = RCM/GCM simulated 2020–2100, obs = observed 1981–2005.

Table 3 Data used in the SWAT model

S. no.	Data	Stations	Duration	Frequency	Sources
Hydro-meteorological data					
1.1	Rainfall	6	1981–2009	Daily	Department of Hydrology and Meteorology, Nepal
1.2	Temperature (max. and min.)	1	1981–2009	Daily	
1.3	Discharge	2	1990–2009/ 2006–2009	Daily	
S. no.	**Data**	**Year**	**Resolution**		**Sources**
Spatial data					
2.1	Digital elevation model (DEM)	2009	30 m		ASTER
2.2	Land use map	2009	300 m		European Space Agency (ESA)
2.3	Soil map	2004	1:10,000,000		SOTER, Nepal

Hydrological model and data inputs

The SWAT developed by the US Department of Agriculture—Agricultural Research Service (USDA-ARS) and Texas A&M AgriLife Research is a physically-based, semi-distributed hydrological/water quality model. The main inputs for the model are meteorological data, land use, land cover, soil properties, and topography (Table 3). The SWAT model forms hydrological response units (HRUs) based on the same land use, soil type, and slope. The HRUs are areas in the watershed which respond similarly to given inputs such as temperature and rainfall (Neitsch et al. 2005). This study uses the daily rainfall data from six stations and maximum and minimum temperatures from one station.

The goodness-of-fit statistics for the evaluation of hydrological model performance

The SWAT model is calibrated and validated at two points: the Melamchi sub-basin and the IRB outlet. The model performance can be assessed using several statistical indicators. For this study Nash–Sutcliffe simulation efficiency (NSE), Percentage Bias (PBIAS), coefficient of determinants (R^2), and ratio of root mean square error to standard deviation (RSR) are used to quantify model accuracy (Eqs. 5–8).

The NSE is one of the most widely used statistical indicators for evaluating the performance of a hydrological model (Shrestha et al. 2013). Its value ranges from $-\infty$ to 1, where 1 indicates a perfect model. The PBIAS helps to indicate the average tendency of the simulated results to be greater or larger than their observed data. The positive and negative results represent the model underestimation and over estimation; hence its optimum value is 0. The R^2 represents the strength of the relationship between observed and simulated values. It ranges from −1 to 1 with the higher value representing better compliance between observed and simulated values. The RSR is the ratio of root mean square error (RSME) to standard deviation (Singh et al. 2004). The higher the RSR values, the lower the model performance; RSR has an optimum value of 0.

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(Q_i - Q_i'\right)^2}{\sum_{i=1}^{n}\left(Q_i - \bar{Q}_i\right)^2} \quad (5)$$

$$\mathrm{BIAS} = \frac{\sum_{i=1}^{n}\left(Q_i - Q_i'\right) \times 100}{\sum_{i=1}^{n}\left(Q_i\right)} \quad (6)$$

$$R^2 = \frac{n\sum Q_iQ_i' - \sum Q_i \sum Q_i'}{\left(\sqrt{n(\sum Q_i^2) - (\sum Q_i)^2}\right) \times \left(\sqrt{n(\sum Q_i'^2) - (\sum Q_i')^2}\right)} \quad (7)$$

$$\mathrm{RSR} = \frac{\mathrm{RMSE}}{\mathrm{STDEV_{obs}}} \quad (8)$$

where, Q_i = measures daily discharge, Q_i' = simulated daily discharge, $\bar{Q}_i$ = average daily discharge for the observed period, $\bar{Q}_i'$ = average daily discharge for the simulated period, n = number of daily discharge values.

e threshold value in goodness-of-fit for the model evaluation was based on Moriasi et al. (2007) (Table 4). This threshold value was used as input in the FITEVAL program developed by the University of Florida (Ritter and Munoz-Carpena 2012) to find the model goodness and probability of it fitting.

Table 4 Model performance rating based on Moriasi et al. (2007)

Performance rating	PBIAS	NSE	RSR
Very good	<±10	0.75	0–0.5
Good	±10 to ±15	0.65–0.75	0.5–0.6
Acceptable	15 to ±25	0.5–0.65	0.6–0.7
Unsatisfactory	>±25	<0.5	>0.7

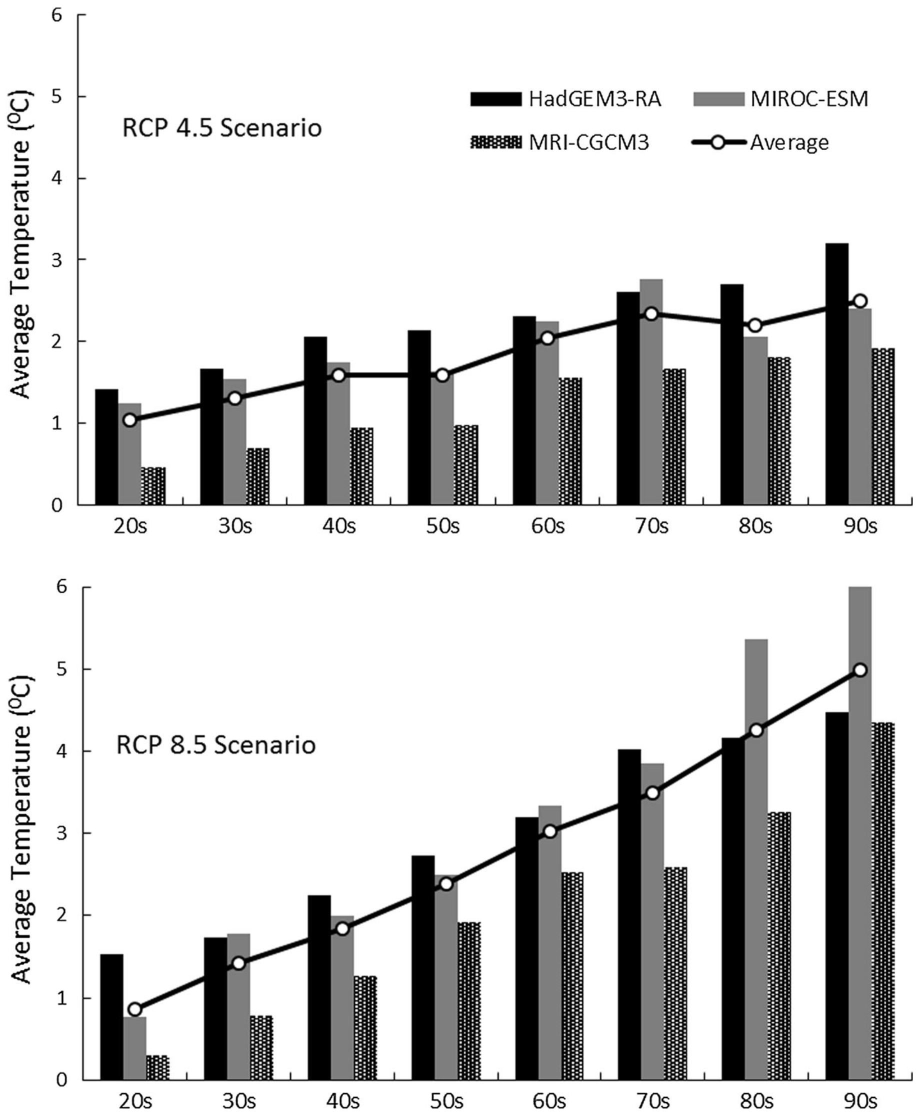

Fig. 3 Changes in the average temperature for different future periods under RCP4.5 and RCP8.5 compared to the baseline period

Results and discussion

Changes in temperature

The bias corrected data for precipitation, as well as maximum and minimum temperatures of three climate models is analyzed in a decadal time frame. For this study, arithmetic mean ensembles of three climate models are analyzed until the 2090s. The future bias corrected precipitation and temperatures are compared with the observed data of the basin. The baseline period considered in this study ranges from 1981 to 2005 for all scenarios.

The change in average temperature of the basin is shown in Fig. 3. The average temperature of the IRB is seen to be increasing under both RCP scenarios. Among all the climate models, HadGEM3-RA shows the maximum increase in temperature under RCP 4.5, whereas under RCP 8.5, MIROC-ESM shows the highest rate of increase in temperature. The ensemble temperature for all models shows an increase of up to 2.5 and 4.9 °C under RCP 4.5 and RCP 8.5, respectively for the 2090s compared to the baseline period. A similar conclusion was also reached by McSweeney et al. in 2010. The change in temperature projected under RCP 8.5 is nearly twice as high as that under RCP 4.5. Overall, temperatures are projected to increase in the future.

Changes in precipitation

Basin-wide precipitation is computed by the Thiessen Polygon method. The projected annual and monthly precipitation for both RCP scenarios and time periods are compared with the observed precipitation of the baseline period for each station.

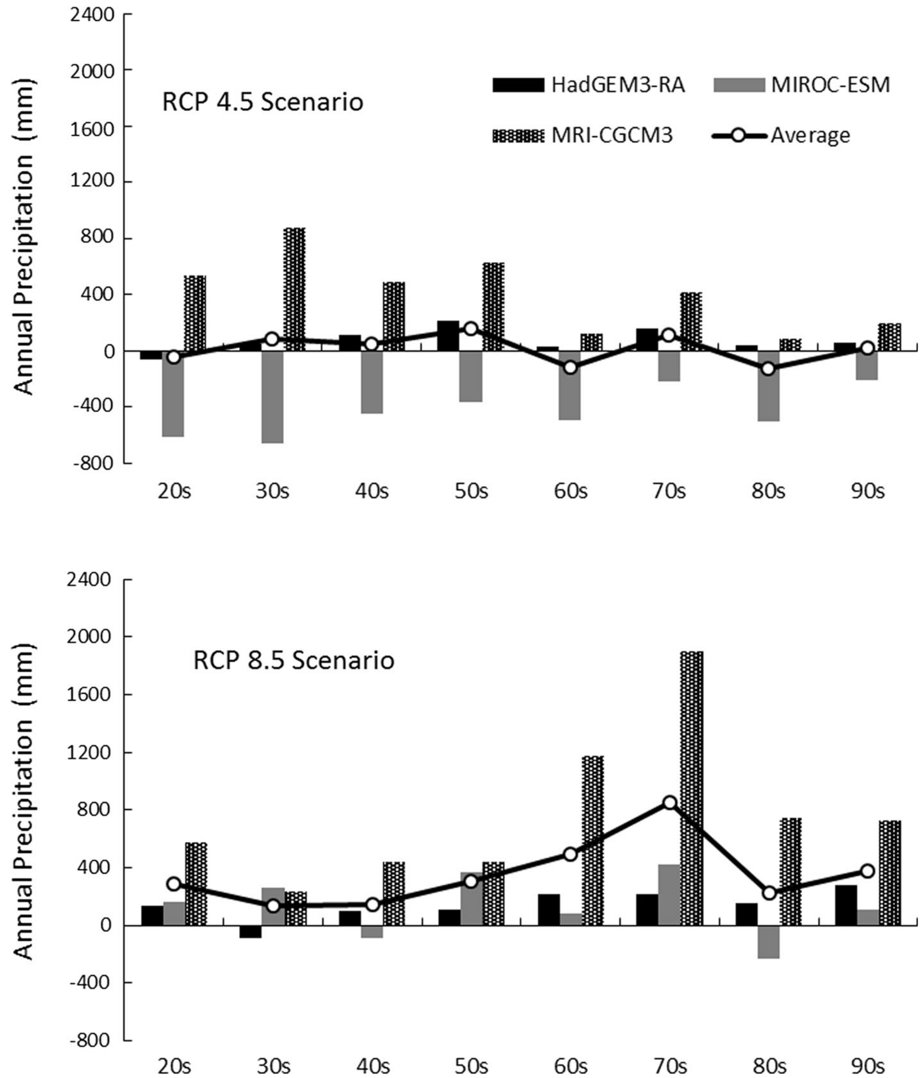

Fig. 4 Changes in the average annual precipitation for different future periods under RCP 4.5 and RCP 8.5 compared to the baseline period

The average change in precipitation of all climate models compared to the baseline period under RCP 4.5 and RCP 8.5 is shown in Fig. 4. The MIROC-ESM under RCP 4.5 shows a decrease in precipitation, whereas among other models MRI-CGCM3 shows the highest increase in precipitation. Under the RCP 8.5 scenario, all climate models show an increase in precipitation. The ensembles of three climate models predict that precipitation in the IRB will decrease by 4.5 and 4.9 % by the 2060s and 2080s, respectively under RCP 4.5, whereas precipitation is shown to increase under RCP 8.5. Precipitation may increase by up to 33 % in the 2070s under the RCP 8.5 scenario. Similar results were obtained by McSweeney et al. in (2010) for annual precipitation changes in Nepal. Overall, average annual precipitation is projected to increase in the future except for the 2020s, 2060s, and 2080s under RCP 4.5, whereas average annual precipitation is projected to increase in all periods under RCP 8.5.

For monthly precipitation changes, future time frames were divided into the 2035s (2021–2040), 2055s (2041–2070), and 2085s (2071–2100). The change in monthly precipitation for different time periods compared to the baseline period is shown in Fig. 5. Under the RCP 4.5 scenario, it is observed that rainfall in the monsoon period increases for the 2035s and 2055s, whereas, it will decrease for the 2085s except in August. However, during pre-monsoon (January–May) precipitation is likely to decrease and may cause a decrease in discharge for the rivers in the study area during the dry period. Under the RCP 8.5 scenario precipitation will increase in the wet period (May–September) for all time frames.

Calibration and validation of SWAT model

The SWAT model is calibrated and validated at two discharge stations. The calibration period for the Melamchi

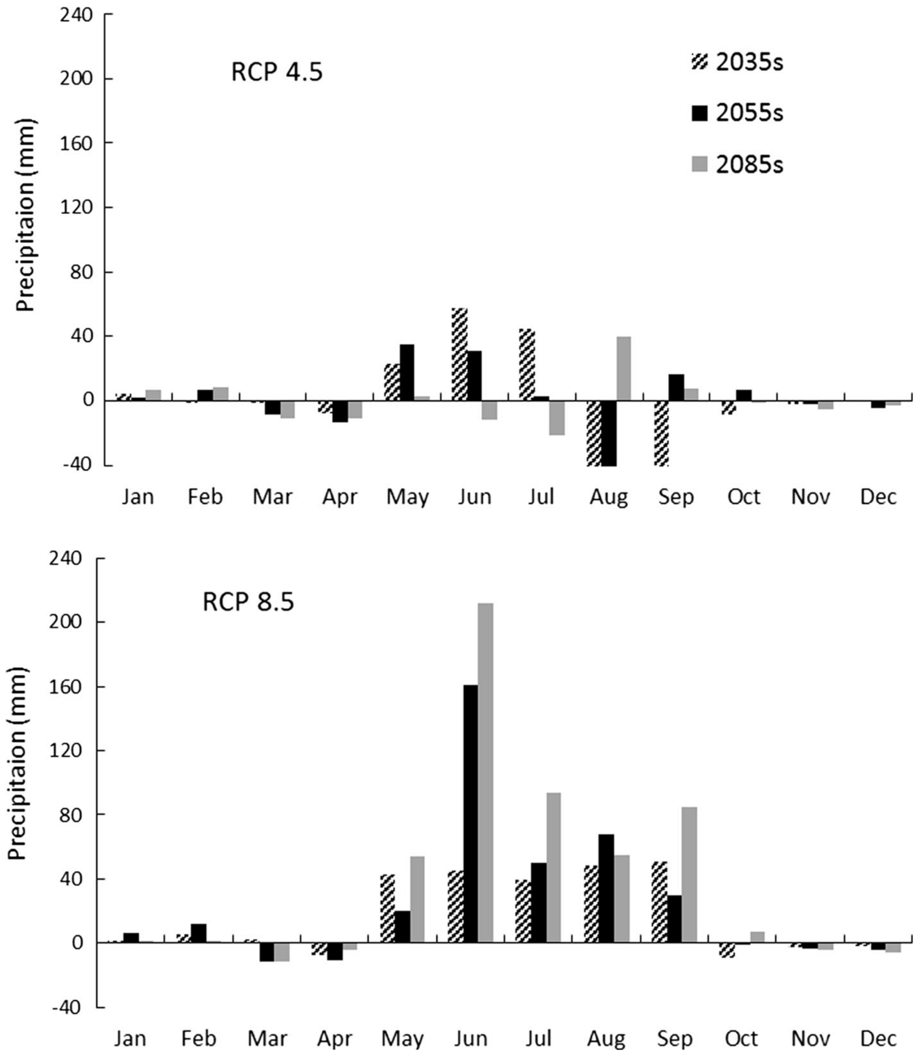

Fig. 5 Changes in the average monthly precipitation relative to the baseline period for different time frames. The average precipitation is calculated as an ensemble of HadGEM3-RA, MIROC-ESM, and MRI-CGCM3

River is from 1988 to 2003 with 4 years of warm-up (1988–1991) and the validation period was from 2004 to 2008. For the Indrawati River, data was only available from 2006 to 2009. This stream flow data was divided as 2006–2008 for calibration and 2009 for validation.

The model performances for the Melamchi sub-basin outlet and the IRB outlet are shown in Figs. 6 and 7, respectively. As indicated by the goodness-of-fit statistics, the model indicates a very good performance.

For the Melamchi sub-basin outlet the model performance was "very good" with both R^2 and NSE being greater than 0.75 and a PBIAS of 2.71 %. However, for the validation period, the model performance decreased to "good" with a probability of it being acceptable at 53.9 % (Table 5). For 2004, the observed data shows a high discharge even with very low rainfall. In addition, for 2006 and 2008, the hydrograph of observed discharge shows very low discharge even with high rainfall. Hence, some errors could have occurred during the measurement process and may be the reason for the model showing satisfactory performance during the validation period. For the IRB outlet, model performance for the calibration period shows "very good" with both R^2 and NSE being greater than 0.80 and the PBIAS at 11.62 %. Similarly, for the validation period, the simulation shows "very good" results with both R^2 and NSE values greater than 0.87 and the PBIAS equal to −3.37 % (Table 6).

Climate change impact on stream flow

The calibrated hydrological model was run for the future climate change scenario in a decadal time frame and the change in discharge calculated with respect to the baseline period. Figure 8 shows the change in percentage of stream flow as predicted by different climate models. All climate models except MIROC-ESM show an increase in discharge for both rivers under RCP 4.5. The discharge decreases by 25 % for the Indrawati River, whereas a 19 % decrease can

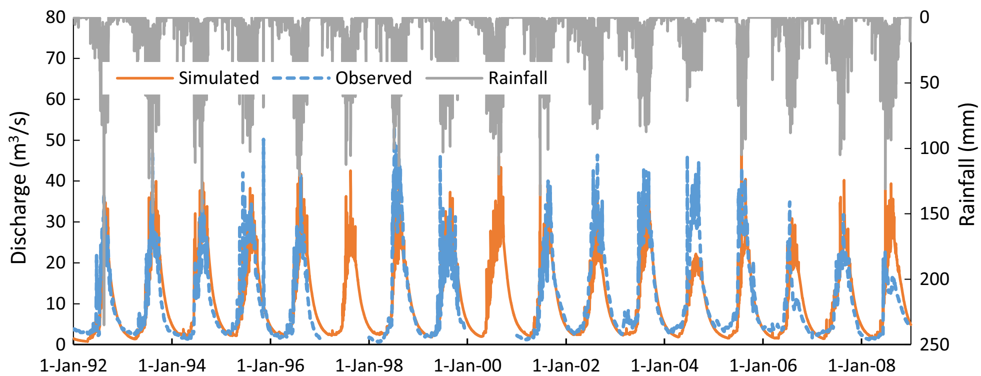

Fig. 6 Comparison of the simulated and observed daily discharge for the Melamchi River

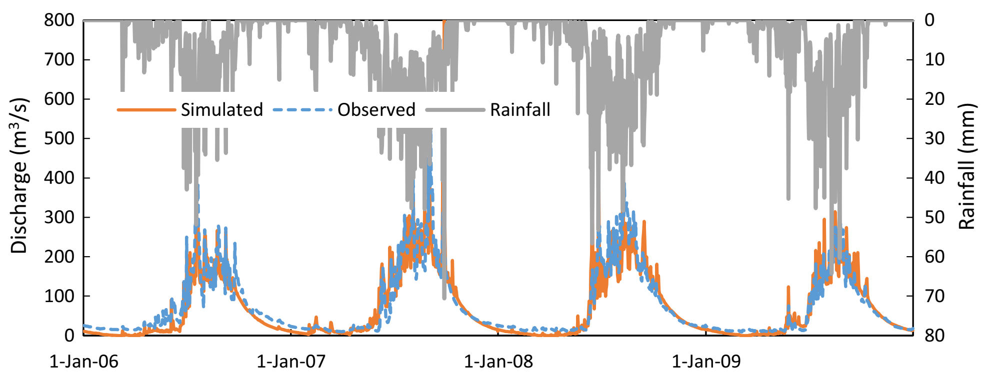

Fig. 7 Comparison of the simulated and observed daily discharge for the Indrawati River

Table 5 Goodness-of-fit statistics of SWAT model for Melamchi River outlet

Period	Time span	R^2	NSE	PBIAS	RMSE (m^3/s)	RSR	Avg Q error	Performance rating	
Observed	1990–2008							Moriasi	FITEVAL
Calibration	1992–2003	0.76	0.76	2.17	4.895	0.48	−2.18	Very good	Very good (72.7 %)
Validation	2004–2008	0.58	0.55	2.15	5.74	0.66	−2.15	Good	Acceptable (53.9 %)

Parenthesis represents probability of being good

Table 6 Goodness-of-fit statistics of SWAT model for the Indrawati River outlet

Period	Time span	R^2	NSE	PBIAS	RMSE (m^3/s)	RSR	Avg Q error	Performance rating	
Observed	2006–2009							Moriasi	FITEVAL
Calibration	2006–2008	0.83	0.81	11.62	38.48	0.44	−11.62	Very good	Very good (96.1 %)
Validation	2009	0.9	0.87	−3.37	24.29	0.36	3.37	Very good	Very good (99.8 %)

Parenthesis represents probability of being good

be seen for the Melamchi River for the 2020s under the RCP 4.5 scenario. Under RCP 8.5, the average annual discharge for both rivers is expected to increase as compared to the baseline period except for the 2080s for the Indrawati River where discharge is likely to decrease by 3 %.

Although there is an increase in average annual discharge, a large variation in monthly discharge can be observed. For the monthly discharge, the time frame was divided into the 2035s (2021–2040), 2055s (2041–2070), and 2085s (2071–2100). The percentage changes in future monthly average flow relative to the baseline period for the Melamchi and Indrawati Rivers under RCP 4.5 and RCP 8.5 are shown in Tables 7 and 8.

The analysis shows that discharge in the Melamchi River will decrease during March to June under RCP 4.5, and for

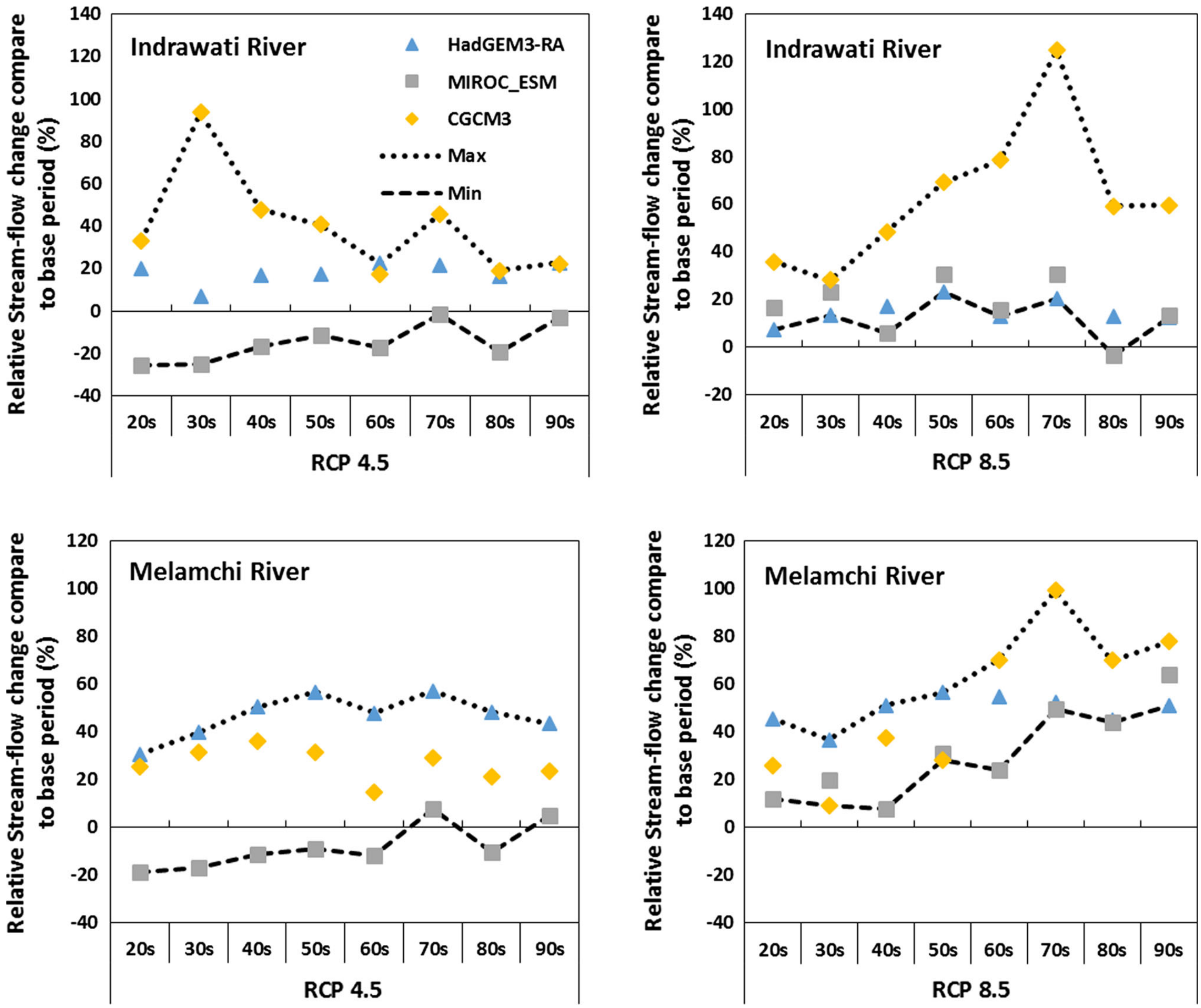

Fig. 8 Projected changes in discharge for the Indrawati and Melamchi Rivers under RCP 4.5 and RCP 8.5 scenarios

Table 7 Percentage change in monthly average discharge in the future under RCP 4.5 and RCP 8.5 scenarios with respect to baseline period for the Melamchi River

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline discharge (m^3/s)												
1990–2008	3.2	2.6	2.8	3.2	4.6	11.0	22.6	26.6	20.8	12.4	7.6	4.6
% Change in discharge under RCP 4.5												
2035s	27.1	6.3	−15.9	−20.2	−13.9	−9.0	−7.7	11.5	35.7	50.1	42.9	42.7
2055s	37.3	12.8	−14.0	−15.2	−4.5	−6.8	−2.6	13.5	47.0	67.3	57.9	55.7
2085s	40.0	13.9	−16.7	−17.3	−8.3	−13.1	−2.8	19.2	51.6	73.0	62.6	58.6
% Change in discharge under RCP 8.5												
2035s	43.2	19.0	−7.3	−13.7	−7.2	−8.5	−5.2	20.2	50.8	68.4	59.7	58.9
2055s	53.1	24.9	−6.6	−5.6	8.8	12.9	12.9	31.4	64.1	89.6	78.0	74.3
2085s	71.8	38.0	1.6	10.0	41.8	43.1	33.0	48.6	85.2	115.8	102.2	95.9

the 2035s under RCP 8.5. The MWSP plans to divert 1.97 m^3/s of water to the Kathmandu Valley with a provision to releasing 0.4 m^3/s of water downstream for environmental flow. The relative decrease in discharge during March and April ranges from −14 to −20 %, indicating potential problems in water diversion into the Kathmandu Valley and downstream discharge. For the months of September to February the discharge will increase, implying that more water can be diverted into the valley.

However, for the Indrawati River, the discharge will increase during the monsoon season and decrease during pre-monsoon and post-monsoon. The increase in discharge during the monsoon season ranges from 4 to 181 %. The decrease in discharge for other months indicates a problem with water availability, especially during the pre-monsoon season.

Table 8 Percentage change in monthly average discharge in the future under RCP 4.5 and RCP 8.5 scenarios with respect to baseline period for the Indrawati River

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline discharge (m^3/s)												
1990−2008	20.4	15.8	14.0	15.1	22.5	67.7	175.9	230.7	176.6	86.2	44.5	26.4
% Change in discharge under RCP 4.5												
2035s	−52.8	−68.8	−66.5	−58.5	28.3	178.0	33.8	8.8	0.5	−5.0	−19.7	−34.8
2055s	−51.7	−59.6	−66.5	−62.9	42.7	86.5	25.6	8.5	14.2	6.9	−10.1	−28.2
2085s	−47.8	−56.1	−68.1	−62.8	4.0	42.9	23.7	20.4	19.4	3.9	−9.1	−27.8
% Change in discharge under RCP 8.5												
2035s	−42.9	−50.6	−50.5	−50.7	52.1	79.1	29.8	24.5	29.3	8.0	−3.4	−20.8
2055s	−40.1	−49.9	−51.1	−46.2	54.6	82.1	36.4	28.1	30.5	10.6	−0.2	−17.1
2085s	−37.8	−49.7	−65.1	−53.9	68.7	181.1	53.2	31.4	31.5	21.0	5.8	−13.9

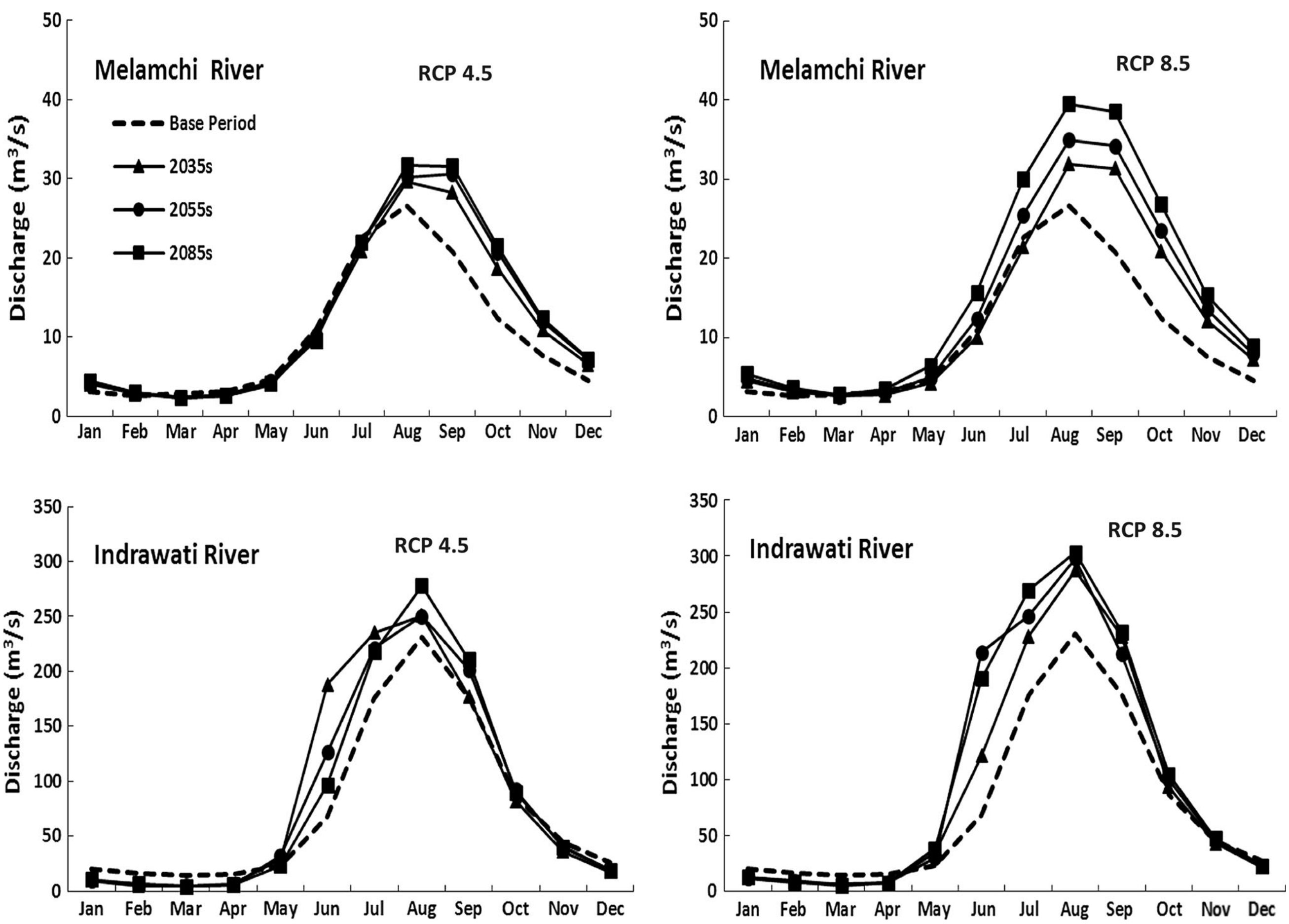

Fig. 9 Projected monthly average discharge for the baseline period and future time periods under RCP 4.5 and RCP 8.5 scenarios. The average discharge is calculated as an ensemble of HadGEM3-RA, MIROC-ESM, and MRI-CGCM3

The average monthly discharge under RCP 4.5 and RCP 8.5 is plotted in Fig. 9 for the Melamchi and Indrawati Rivers. From the hydrograph, it can be observed that under the RCP 4.5 scenario, there is a decrease in discharge for the Melamchi River in the month of March. In addition, the discharge into the river from February to April is enough to divert water into Kathmandu Valley after releasing 0.4 m^3/s downstream as an environmental flow requirement.

Summary and conclusions

The main objective of this study is to find changes in the future climate and its impact on the hydrology of the IRB in Nepal. This study can provide water resources management or policy makers with a wide range of results for plausible future climate scenarios in the context of climate change in the IRB. Three CMIP5 climate models for two RCP scenarios were used to address the uncertainties in projecting the future climate of the IRB. The data was bias corrected and used in a hydrological model, SWAT, to simulate future changes in water availability in the basin. The future period from 2021 to 2100 was divided into decadal time frames to investigate the potential impact of climate change on hydrology and water resources.

The bias corrected data from all climate models shows good agreement with the observed data in terms of R^2, RMSE, mean, and standard deviation. It is found that the average temperature of the basin will rise continuously and will increase by 2.5 to 4.9 °C by the end of the century compared to the base period. However, precipitation shows no definite trend. The annual precipitation is likely to increase but decrease during the 2060s and 2080s under the RCP 4.5 scenario. In contrast, under RCP 8.5, precipitation will increase in the future.

Annual discharge is projected to increase in the future for both the Melamchi and Indrawati Rivers. This implies that more water can be diverted to the Kathmandu Valley. However, the monthly analysis reveals that there will be a significant decrease in discharge into the Melamchi River during the months of March and April. This implies that the water in the river will be just sufficient to divert water to Kathmandu Valley during these months. The discharge in the Indrawati River will increase during the monsoon season and decrease during the pre-monsoon and post-monsoon periods. The results of this study may be useful for understanding the potential impact of climate change and the formulation of adaptation strategies to offset the negative and harness the positive impacts of climate change in the basin.

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