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Adapting hydropower production to climate change: A case study of Kulekhani Hydropower Project in Nepal

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ABSTRACT

Hydropower is one of the reliable and clean sources of energy helping in climate change mitigation, nevertheless, its generation is impacted by climate change. Therefore, this study aimed to assess the impact of climate change on the Kulekhani Hydropower Project (KHP), Nepal and evaluate the adaptation options to maximize hydropower generation under climate change scenarios. Three Regional Climate Models (RCMs) namely ACCESS, CNRM and MPI were bias-corrected by linear scaling method for future periods of 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099) with the baseline period of 1976–2005. The increase in maximum and minimum temperatures were found to vary from 0.4–3.8 °C and 0.4–4.2 °C respectively with a magnitude of rise higher for the Representative Concentration Pathway (RCP) 8.5 scenario. However, precipitation was found to be erratic showing no specific trends but rather found to increase in the dry season and decrease in the wet season, along with the shifts in the time of peak. Additionally, hydrological models were used to simulate future discharge and hydropower generation under climate change scenarios. Besides, the hydropower generation was projected to decrease by 0.5–13% for different periods compared with the baseline. Further, several reservoir rule curves were examined as an adaptation option to minimize the impacts of climate change on hydropower generation and it was found that the modification of existing rule can offset the negative impacts. The results of this study will be helpful for KHP authority to revise the operation and management of reservoir for sustainable hydropower production.

1. Introduction

Predominantly, hydropower projects in Nepal are run-of-the-river (RoR) type due to which there is a vast decline in their output during the dry season. The Kulekhani Hydropower Project (KPH), a cascade of three hydropower projects, holds a major role in purveying a sustained supply of electric power. Presently, Kulekhani Hydropower Project-I (KHP–I) (60 MW) and Kulekhani Hydropower Project-II (32 MW) are the existing operational hydropower projects whereas Kulekhani Hydropower Project-III (14 MW) is under construction. The KHP–I was designed to generate an annual primary and secondary energy of 165 GWh and 46 GWh respectively (NEA, 2018). Moreover, it is used to induce black start in the Integrated Nepal Power System during the national power system collapse (NEA, 2018) and was also designed to serve as an emergency standby station during the peak load (Shrestha et al., 2014). However, hydropower projects including KHP have been facing several challenges such as declination in performance, operation and maintenance of the reservoir, sedimentation each passing year, and decrease in water availability due to climate change during its lifecycle. Hence, climate change acts as a prime stressor that affects the river hydrology and eventually hydropower projects.

Climate change has been accelerated by different anthropogenic activities across many regions around the globe influencing the hydrological cycle and affecting the water resources management as a whole (Shrestha et al., 2016; Yang et al., 2016). Moreover, alteration in water availability due to variations in precipitation, rise in temperature, increase in evaporation rate, and glacier meltdown further aids to escalate the frequency of extreme

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hydrological events (Qin et al., 2020). Besides, climate change has been projected to alter both spatial and temporal distribution of water availability (Yang et al., 2016), with some river basins receiving less while others receiving more precipitation (Turner et al., 2017). Any changes in these two factors are likely to fluctuate the seasonal flow of the river leading towards the variations in the hydropower generation, due to the imbalanced trade-off between contradicting objectives of reservoir operation (Yang et al., 2016). As a consequence, the fluctuation in streamflow distribution was projected to reduce the net global hydropower generation and operation under Representative Concentration Pathways (RCP) 2.6 and RCP 8.5 towards the end of the century (Wang et al., 2019; van Vliet et al., 2016). However, some regions of India, Northeastern China, Canada, Central Africa, and Northern Europe are expected to have increase in future hydropower generation (Turner et al., 2017; Liu et al., 2016). Moreover, studies on climate change conducted in the European Alps and Western U.S. shows a decline in hydropower generation due to the decreasing mean annual runoff and seasonal runoff. Similarly, the hydropower generation was found to increase in winter and decrease during the summer (Koch et al., 2011). Several countries depending on hydropower for electricity, water supply, and food cultivation are expected to face problems due to the decrease in the availability of water. Hence, effective and sustainable use of water is required. Additionally, there has been an increased impact of climate change in developing countries as compared to the impact on developed countries due to the lack of advancement in technological and economic sectors (Berga, 2016; Shrestha et al., 2016; Khan et al., 2013).

Nepal has the second-largest reserve for surface freshwater in the world with the existence of large number of perennial rivers, contributed by monsoon precipitation, glaciers and snow melting of higher regions, flowing in the variations of topography ranging from 60 masl to 8848 masl (Sharma and Awal, 2013). The large variance in the topography along a short distance makes Nepal a suitable space for hydropower generation. On the other hand, the same aspect leads to a large variation in the climate throughout the country making hydropower generation vulnerable to climate change. Nevertheless, being a renewable and clean source of energy, the country highly depends on hydropower production for the generation of electricity (ADB, 2017). Therefore, the climate change impact analysis on hydropower generation holds a significant role for Nepal. Further, the spatial-temporal variation affects both storage as well as RoR type of hydropower plants but the former being flexible due to its storage capacity whereas the latter is sensitive towards any changes in climate as it directly depends on the flow availability at that instant (Hamududu and Killingtveit, 2012; Koch et al., 2011). Likewise, snow and glaciers being the enormous sources of natural freshwater, has been retreating at a faster rate due to the higher rate of rise in temperature in the higher elevations of Nepal (Singh et al., 2011; Bagale, 2017). Furthermore, rise in temperature in the winter was found to be noticeably higher (0.06–0.08 °C per year) than the warmer months (0.02–0.05 °C per year) throughout Nepal (Singh et al., 2011). Leading to shifts in the time of peak discharge, increase in the duration of peak discharge, shift in the form of precipitation from snow to rainfall as well as an upward shift in the snowline resulting in high fluctuation in the generation of hydropower.

River basins consisting of hydropower plants are likely to face higher risks with regards to future climate change and variation. Hence, there is an urgent need to understand the future hydrological changes that affects the sustainability of hydropower production and should be forethought to formulate and accustom the current policies as well as adaption measures of the hydropower plants (Zhong et al., 2019). Hydropower plants have been found to be environment friendly and producing a trivial amount of greenhouse gases (Li et al., 2019). However, different structural and non-structural measures must be applied in order to manage the climate change impact on hydropower plants. Operation and management strategies with respect to the future hydro-climate is necessary to adapt to the challenges in reservoir management (Zhou and Guo, 2013) as they are critical in snow-fed watersheds. Shifts in peak and variability in winter discharge can make the reservoir vulnerable (Arsenault et al., 2013). According to the study done in Canada and USA, climate change was found to have a serious impact on the reservoir performance of a basin (Payne et al., 2004; Minville et al., 2010; Vonk et al., 2014). So, an adaptive basin-wide operating rule curve is required in order to protect the downstream ecosystem for sustainable water use (Zhou and Guo, 2013). However, these non-structural measures may not be sufficient to tackle with foreseeable climate change impacts. Therefore, structural measures such as amendment of spillways, tunnels/canals, number of turbines in addition to construction and customization of reservoir dimension are necessary to make a safe environment to the population depending on hydropower (Haguma et al., 2017).

Further, climate change impact has a huge influence on the hydropower generation of all the hydropower projects as it could even lead to events such as power cut-offs which started off in 2008, where the country went through a 14–16 h of load shedding in the dry season of 2015 and 2016 (Timilsina et al., 2018). The industrial demand of Nepal currently is 3000 MW whereas the country has its installed capacity of only 753 MW (Timilsina et al., 2018). Since the demand does not meet supply, the government of Nepal has been emphasizing on reservoir-based hydropower plants which have to be insured with respect to the repercussions of climate change. Therefore, this study aims to project the future climate under different RCP scenarios and its impact on the hydropower production of the Kulekhani Hydropower Project in Nepal. Thereafter, this study analyzes the adaptation options to offset the negative impacts of climate change on hydropower generation.

The paper has been organized into four sections. The first section, the introduction, highlights the importance of the study. Section 2, materials and methods, describes the study area, data collection, and research design. Section 3, results and discussion, provides the significant results of the study and its interpretation. The final section is the conclusions which also provides some implications of the findings.

2. Material and methods

2.1. Study area

The KHP–I, situated in the Bagmati River Basin of Nepal, was selected as a case study to evaluate the effects of change in climate on hydropower generation. Fig. 1 illustrates the location map, layout, and schematic diagram of KHP–I. It has its location ranging between 27°30′00″N and 27°40′46″N latitude and 85°1′41″E and 85°13′56″E longitude, having a total watershed area of around 126 km^2 (Shrestha et al., 2014). The project area lies 30 km southwest of the capital city, Kathmandu, in Makwanpur district of central development region (NEA, 2018; Timsina et al., 2019). It includes two basins namely Kulekhani River Basin (KRB) and Upper Rapti River Basin (URRB). This project is the only reservoir-based hydropower till date in the country, supplying electricity during the peak demand period of the day and when the RoR based hydropower cannot run with its full capacity due to decreased discharge in the river during the dry season. Therefore, the water is stored during the wet season (June–September) and used for the hydropower generation in the high demand dry season (October–May). The wet season from June–September and dry season

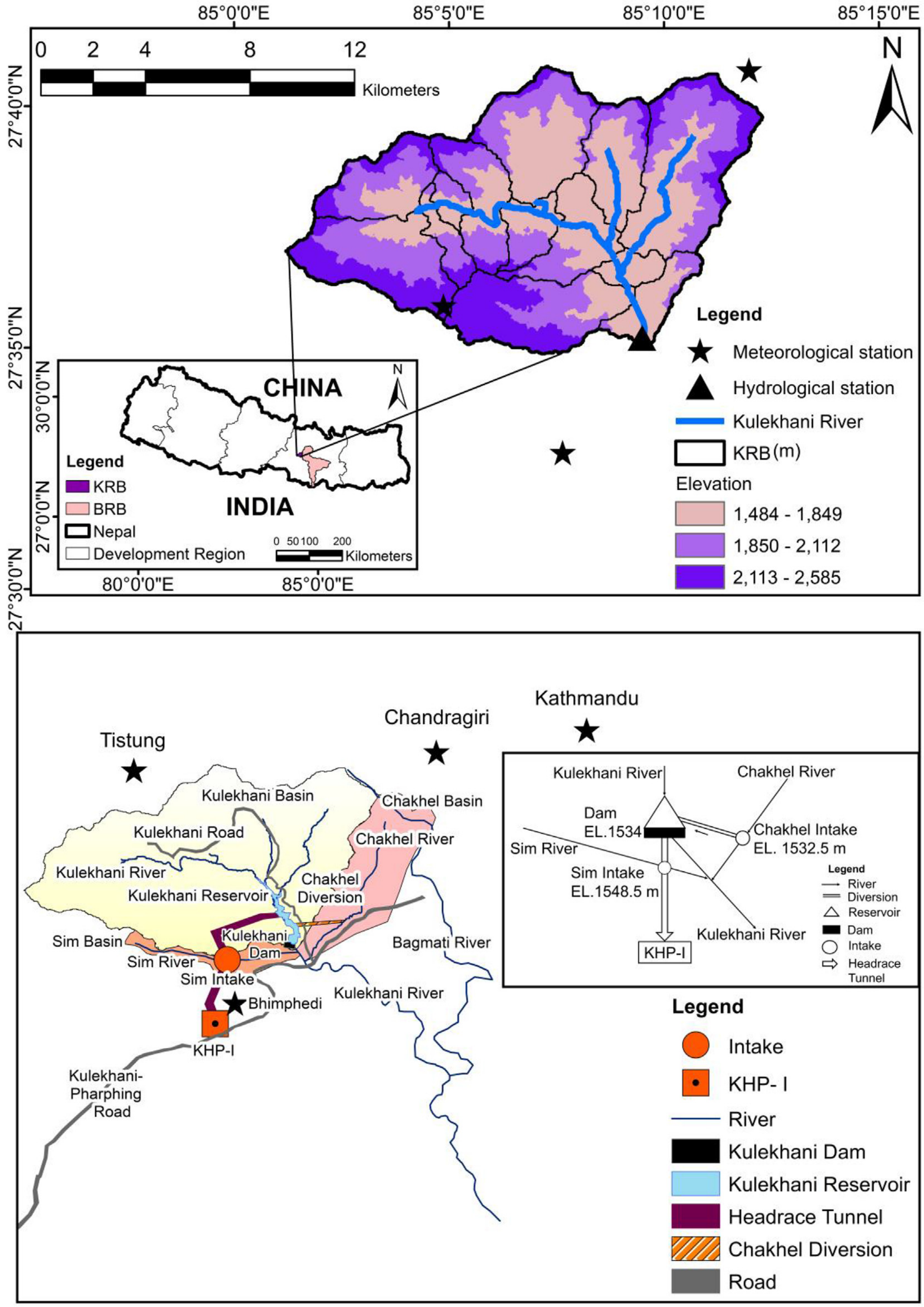

Fig. 1. Location map, layout and schematic diagram of KHP–I and hydro-meteorological stations in Bagmati River Basin, Nepal.

from October–May have been considered for this study (Dahal et al., 2020). An extensive monsoon rainfall is found in the physiographic region where the KRB is located. Further, meteorological and hydrological stations selected for this study are depicted on the location map in Fig. 1.

Kulekhani watershed is divided into 8 sub-watersheds each of which having discrete drainage collected in the 7 km long and 2.2 sq. km area of the reservoir, Indra Sarobar having a total storage capacity of 85.3 million m^3 with 73.3 million m^3 of live storage and 12 million m^3 of dead storage, created by its dam (Shrestha et al., 2014). It has its dam, 114 m high rock-filled dam, located in KRB whereas the underground powerhouse is located in the URRB at an elevation of 900 m. The reservoir is fed by the Kulekhani river, annual average discharge of 6.2 m^3/s and 2.1 m^3/s in the wet and dry season

(Shrestha et al., 2014), as well as by two of its tributaries namely, Chakhel and Sim river (Nippon Koei Co., Ltd., 1982). According to Nippon Koei. Co., Ltd (1982), Chakhel river, with the catchment area of about 23 km^2 and an annual average discharge of 0.71 m^3/s, joins the Kulekhani river 5 km downstream of the dam site. This river is diverted to the reservoir at an elevation of 1532.5 m and 3.5 km northeast from the dam site through a connecting tunnel. Sim river, with the catchment area of 7 km^2 and an annual average discharge of 0.4 m^3/s, joins the underground headrace tunnel at 1.9 km downstream from the dam with the intake at an elevation of 1548.5 m, above dam elevation of 1534 m. As a result, when there is no supply of water for the hydropower generation the water from the Sim river is diverted back to the reservoir for storage through the same headrace tunnel as the elevation of the sim intake is higher than the full reservoir level. The headrace tunnel and penstock pipe of length 6 km and 1.3 km respectively conveys water from the reservoir to the powerhouse for the hydropower generation. Which is later released to Mandu river, a tributary of Rapti river, through a 1 km tailrace tunnel (Shrestha et al., 2014). Further, the salient features of KHP—I have been illustrated in Table 1.

2.2. Data

2.2.1. River basin data

The river basin information required as an input in Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012; Betrie et al., 2010), such as Digital Elevation Model (DEM) (Hawker et al., 2019; Li et al., 2017) of 30 m resolution, an information on the elevation at any specific point, was acquired from the Central Department of Survey, Nepal. Likewise, land use map of 300 m resolution for 2010 was obtained from the European Space Agency (ESA) website (http://www.esa.int/). The Soil and Terrain Database Programme (SOTER) (https://www.isric.org/explore/soter), was used to acquire the soil map of scale 1:5000000.

2.2.2. Hydrological and meteorological data

Daily hydrological data of station no. 570 of Kulekhani river was obtained for a time period of 1969—1976 from the Department of Hydrology and Meteorology (DHM), Nepal. Daily observed precipitation data starting from 1969 to 2005, available at three stations, Chisapani Gadhi, Thankot and Daman were acquired from the DHM, Nepal. Due to the availability of only one precipitation station inside the KRB, the nearest two stations available at an immediate boundary of the basin were considered for this study. Daily maximum and minimum temperature data available only for Daman station for the same duration also was acquired. Whereas, the projected future Regional Climate Model (RCM) data for three RCMs namely: ACCESS-CSIRO-CCAM (ACCESS), CNRM-CM5-CSIRO-CCAM (CNRM) and MPI-ESM-LR-CSIRO-CCAM (MPI) from 1965 to 2100 were downloaded from South Asia CORDEX data portal (http://cccr.tropmet.res.in/home/index.jsp).

Table 1
Salient features of KHP—I.

Characteristics	KHP—I
Type	Storage
Location	Dhorsing, Makwanpur
Installed Capacity	60 MW
Rated Head	550 m
Catchment area	126 km^2
Design Discharge	12.1 m^3/s
Total Storage	85.3 million m^3
Live Storage	73.3 million m^3
Dead Storage	12 million m^3
Reservoir Surface Area	2.2 km^2
High Water Level (HWL)	1530 m
Low Water Level (LWL)	1476 m
Tail Water Level (TWL)	916 m
Dam Type	Zoned Rockfill Dam with Inclined core
Dam Height	114 m
Dam Crest Elevation	1534 m
Dam Crest Length	406 m
Turbine:	
No. and Type	Two, Vertical Shaft Pelton
Rated output	31 MW
Rated speed	600 rpm
Generator:	
Rated Capacity	35 MVA
Generated Voltage	11 KV
Frequency	50 Hz
Commissioned Date	May, 1982

2.2.3. Reservoir and hydropower data

Reservoir and hydropower data necessary for the Hydrologic Engineering Center's Reservoir System Simulation (HEC-ResSim) model, reservoir operation and hydropower generation data from 1982 to 2009, were acquired from the Nepal Electricity Authority (NEA), Nepal. These data were used for the projection of the hydropower generation and modification of the reservoir rule curve. Additionally, list of the collected data for the study have been illustrated in Table S1 of the supplementary table.

2.3. Methodology

The target of this study was to estimate the impact of climate change on the future hydropower generation of KHP—I under different climate change scenarios. In addition, it includes the sub-processes such as bias correction of RCMs by linear scaling bias correction method, climate change projection, hydrological analysis using SWAT, and reservoir simulation by HEC-ResSim. Fig. 2 depicts the overall methodological framework adopted for this study.

2.3.1. Projection of future climate scenarios

The climate models chosen, in this study, were ACCESS, CNRM, and MPI as stated in section 2.2.2 for three climate variables minimum temperature, maximum temperature, and precipitation. The RCMs were chosen based on its resolutions and these RCMs were also found to be used in the basins of Nepal (Budhathoki et al., 2020; Shrestha et al., 2020). Along with assessments on the performance of CORDEX by Ghimire et al. (2015). The aforementioned climate models were chosen under two emission scenarios, i.e. RCP 4.5, an intermediate scenario, and RCP 8.5, a worst-case scenario, amongst the four existing scenarios as per the fifth assessment report of the Intergovernmental Panel on Climate Change. While RCP 2.6, the best-case scenario which considers the reversal in the use of fossil fuels is near to impossible for today's world, and RCP 6, an intermediate scenario which is similar to RCP 4.5 were not taken into consideration.

Although RCMs data have been successful to imitate baseline climate data at a large scale, they are certain to fail at the basin level study due to its biasness (Shrestha et al., 2017). Moreover, impact assessment is impeded, so, prior to the impact assessment, it must further be corrected by bias correction method so as to predict the climate parameters closer to the actual conditions (Teutschbein and Seibert, 2010). Hence, the linear scaling bias correction method was applied for its simplicity in application with accuracy almost equal to the complex and tedious methods (Shrestha et al., 2017). The correction factors obtained from observed and simulated data were applied to obtain the corrected climate data. The following equations were used for linear scaling method (Shrestha et al., 2020):

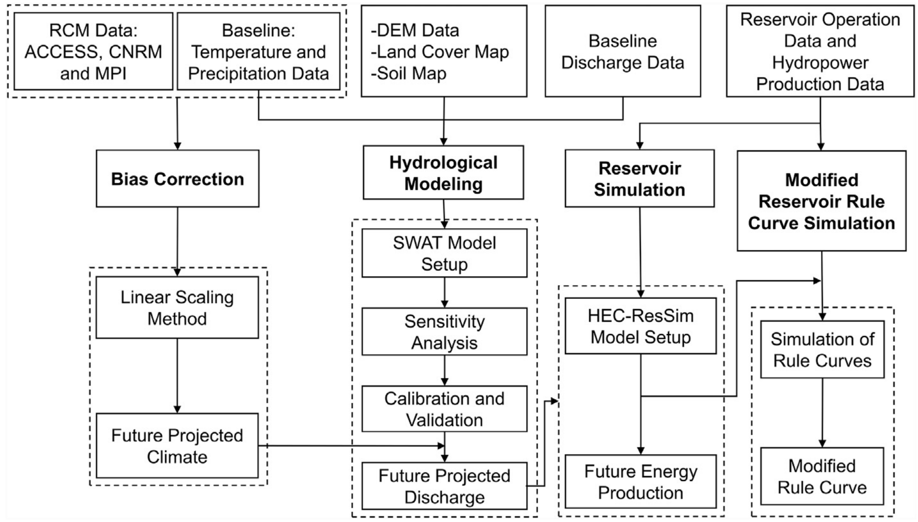

Fig. 2. Overall methodological framework adopted in this study.

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

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

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

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

Where, P is the precipitation, T is Temperature, d stands for daily, μ_m specifies the long-term monthly mean, an asterisk (*) indicates bias corrected value, his refers to historical raw RCM data, obs stands for observed data and sim is the raw RCM future data for equation (1) to equation (4).

The performance evaluation of the bias correction method was done based on four statistical indicators such as coefficient of determination (R^2), standard deviation (σ), root mean square error and mean of temperature as well as precipitation. The performance evaluation was based on the daily data for the baseline period of 1976–2005. Projected RCM data from 2006 to 2099 was considered after the bias correction, for the analysis, which was further sectioned into three periods of 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099) under RCP 4.5 and RCP 8.5 scenario.

2.3.2. Hydrological modeling

The SWAT is a comprehensive, physical-based, semi-distributed, continuous-time hydrological model developed by the United States Department of Agriculture-Agricultural Research Services (Palazzoli et al., 2015; Neitsch et al., 2011), capable of simulating surface flow, sediment deposition, nutrient movements and sub-surface flow (Arnold et al., 1998). SWAT works on a daily time step (Arnold et al., 2012), therefore, it was selected for the hydrological modeling of this study, as it is the requirement of the succeeding processes. Besides, it was found to perform successfully for the river basins of Nepal such as Kaligandaki Basin and Upper Tamakoshi (Bajracharya et al., 2018; Shrestha et al., 2016). ArcSWAT, an extension of SWAT for ArcGIS software, was used to set-up the model for the hydrological process of the KRB. The SWAT requires a computer program interface (ArcSWAT) and digital map-formatted information such as DEM, land use map, soil use map, baseline discharge, temperature and precipitation data along with projected temperature and precipitation data. Further, the water balance equation (Neitsch et al., 2011) for the hydrological simulation in SWAT is as follows:

$$SW_t = SW_o + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \tag{5}$$

Where, SW_t denotes the soil water content (mm) at the end of time step t (days), SW_o denotes the initial soil water content in day i (mm), R_{day} denotes the amount of precipitation on day i (mm), Q_{surf} refers to the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm) and Q_{gw} is the amount of base flow from the shallow aquifer on day i (mm).

Firstly, in the model setup process, the watershed was delineated using DEM which was subdivided into 13 sub-basins. Further, the sub-basins were divided into 72 hydrological response units (HRUs). HRUs are portions of land within the sub-basin consisting of the combination of unique land cover, soil, and slope (Palazzoli et al., 2015; Arnold et al., 2012). The SWAT model was run for 8 years on a daily time step with a warm-up period of 3 years (1969–1971), calibration period of 3 years (1972–1974) and validation period of 2 years (1975–1976).

Sensitivity analysis is the method to ascertain the rate of change in the model output with reference to the changes in the model input parameters (Arnold et al., 2012). It was carried out to increase the model performance and decrease uncertainty present in the model generated for KRB. As suggested by Abbaspour, the parameters are categorized as sensitive if the p-value is less than 0.05 (Abbaspour et al., 2015). Based on the P-value, 21 different parameters were found to be sensitive which have been used for calibration of the model of KRB. The identified sensitive parameters and their fitted values are listed in Table S3 of the supplementary table. After the sensitivity analysis, those 21 parameters were taken for the calibration process by auto-calibration in SWAT-CUP. Calibration was followed by validation taking an independent dataset to check if the model was performing well enough.

2.3.3. Evaluation of hydrological model

In order to ensure the precision and accuracy of the SWAT model and to authenticate the robustness of the model, evaluation of the model was carried out with four statistical indices namely coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), percentage bias (PBIAS) and the ratio of mean squared error to the standard deviation of the measured data (RSR). The model performance is acceptable if the R^2 and NSE values are greater than 0.5, PBIAS values are within ±25% and RSR values are less than 0.7 (Betrie et al., 2010; Moriasi et al., 2007). The performance of the model was carried out based on the annual daily discharge and seasonal discharge.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{mean}\right)^2}\right] \tag{6}$$

$$R^2 = \frac{n\sum Q^{obs}.Q^{sim} - \sum Q^{obs}.\sum Q^{sim}}{\left(\sqrt{n\left(\sum Q^{obs2}\right) - \left(\sum Q^{obs}\right)^2}\right) \times \left(\sqrt{n\left(\sum Q^{sim2}\right) - \left(\sum Q^{sim}\right)^2}\right)} \tag{7}$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{mean}\right)^2}} \tag{8}$$

$$PBIAS = \frac{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right) \times 100}{\sum_{i=1}^{n}\left(Q_i^{obs}\right)} \tag{9}$$

Where, Q_i^{obs} is the observed discharge for the i^{th} time, Q_i^{sim} is the simulated discharge for i^{th} time, and Q_i^{mean} is the mean discharge for i^{th} time. Q^{Obs} is the observed discharge, Q^{Sim} is the simulated discharge, n is the number of observations for the equations.

In addition, the Flow Duration Curve (FDC) was further used for the model performance evaluation. FDC is the graphical representation of the availability of the amount of flow for a discrete percentage of time (Sidek et al., 2013; Bonta and Cleland, 2003). FDC clearly depicts different hydrological indicators and further helps in the evaluation and better analysis of the model based on the different flow regimes. It was used to determine the performance of the model based on the high flow, medium flow, and low flow.

2.3.4. Reservoir simulation

The HEC-ResSim is a widely used simulation model developed by the Hydrologic Engineering Center of the US Corps of Engineers. It is a well-established and widely used model for the simulation of reservoir systems within basins (Klipsch and Hurst, 2013). This model is used to replicate the performance of the reservoir in different conditions and assist in smooth reservoir operation even during emergency conditions. In the current study, HEC- ResSim was used to project the hydropower generation capacity of KHP–I for three future periods 2020s, 2050s, and 2080s under RCP 4.5 and RCP 8.5 scenario and compared with the baseline period of 1982–2009. It takes the daily streamflow data projected from the SWAT model, baseline reservoir operation data, baseline power generation data, physical reservoir characteristic data, energy characteristic data, and operational data for different zones of the reservoir. Basically, HEC-ResSim has three modules namely watershed setup, reservoir network, and simulation module. Each module providing access to specific types and directories of the data within the watershed data tree (Klipsch and Hurst, 2013). Also, HEC-ResSim uses HEC-DSS as a data storage system for the storage and retrieval of the input and output data. Additionally, the governing equations for reservoir simulation in HEC-ResSim are as follows (Klipsch and Hurst, 2013):

$$T_s = \frac{KTS}{Q^n} \tag{10}$$

Where, T_s is time of storage per increment in hours, KTS is the constant determined by trial and error or estimated from physical measurements of flow and corresponding routing times, Q is discharge in Cubic meters per hour and n is coefficient usually between −1 and 1.

The continuity equation:

$$I - O = \frac{ds}{dt} \tag{11}$$

Where, I is the inflow rate, O is the outflow rate, s is the storage and t is the routing time interval.

Power equation:

$$P = \eta * \rho * Q * g * h \tag{12}$$

Where, P is the power in watts (W), η efficiency of the turbine (dimensionless), ρ density of water (1000 kg/m^3), Q rate of flow (m^3/s), g acceleration due to gravity (9.8 m/s^2), h is the head difference between reservoir level and tailwater (m).

Hydropower generation equation:

$$E = \text{Power (P)} * \text{Time (t)} \tag{13}$$

Where, E is the energy generated in Watt-hour (Wh), P is power in watt (W) and t is time in hour (h).

2.3.5. Modification of the reservoir rule curve for maximizing hydropower generation

The KHP–I have still been using the rule curve designed at the initial phase of its construction in 1982 as stated in section 1. Climate change has a substantial impact on hydropower generation as it results in the fluctuation of the flow. Accordingly, it is required to adapt to a modified rule curve emphasizing a separate rule curve for the different time periods as climate change impact varies. So, for the purpose of maximization of the rule curve, trial and error simulation method was used for this study in HEC-ResSim. Ten different rule curves were chosen for the trial and error to find out the favorable rule curve for the Kulekhani reservoir. In order to find out the most feasible rule curve for the maximum possible generation of hydropower, ten different rule curves were chosen based on the pattern of precipitation, shifts in the time of peak, and change in the amount of discharge in different time periods.

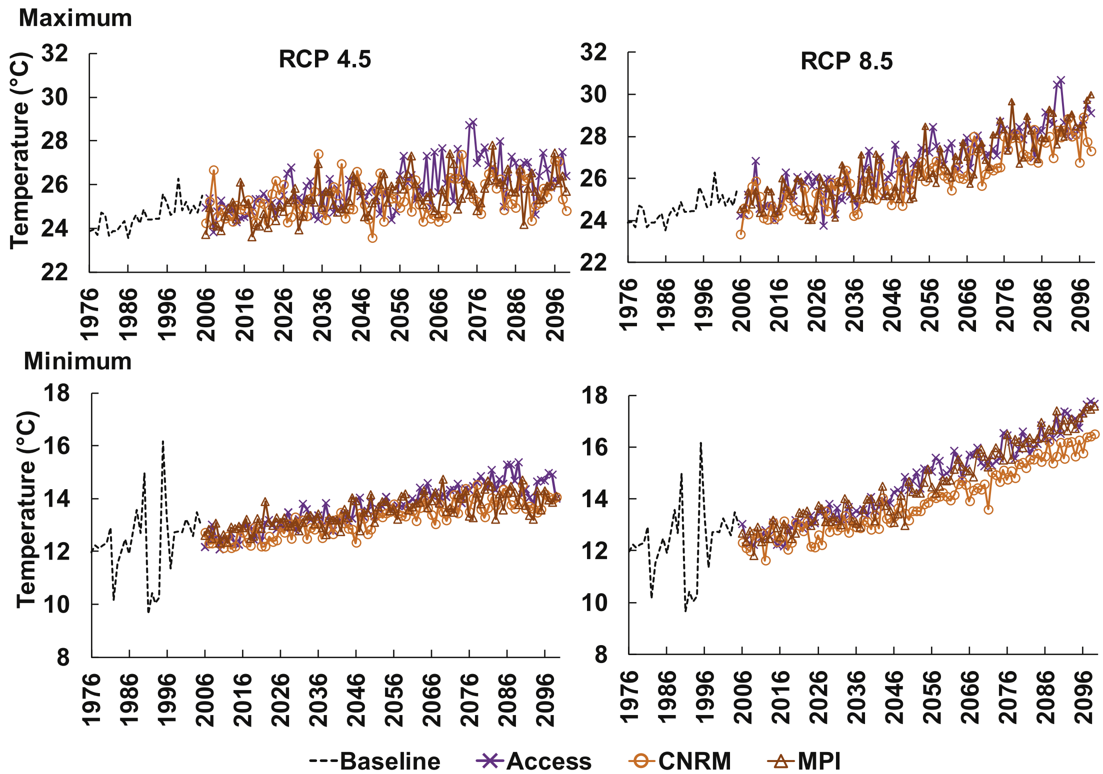

Fig. 3. Maximum and minimum temperature projected under RCP 4.5 and RCP 8.5 scenario from 2006 to 2099 compared to the baseline period of 1976–2005 for Daman station.

3. Results and discussion

3.1. Analysis of the projected temperature and precipitation

The maximum and minimum temperature both are projected to increase under RCP 4.5 and RCP 8.5 scenario for all three RCMs until the end of 2099, having the magnitude of increase comparatively higher for RCP 8.5 and following continuously increasing trends similar to the baseline period of 1976–2005, illustrated in Fig. 3. The baseline maximum temperature is observed in range between 23 and 26 °C which is projected to range between 24–29 °C and 24–31 °C under RCP 4.5 and RCP 8.5 scenario respectively. Moreover, the greatest rise of 29 °C in 2075 under RCP 4.5 and 31 °C in 2091 under RCP 8.5 is projected by ACCESS. Likewise, baseline minimum temperature is observed to range between 10–16 °C whereas the same is projected to range between 12–15 °C and 12–18 °C under RCP 4.5 and RCP 8.5 respectively. Correspondingly, the maximum increase of 15 °C in 2089 under RCP 4.5 and 18 °C in 2098 under RCP 8.5 are also projected by ACCESS. Further, Fig. 4 depicts the change in maximum and minimum temperature. In case of RCP 4.5, it depicts similar trends of increase for both minimum and maximum temperature in all RCMs, with an increase within 0.5–2.5 °C in all periods considered. Although same is not the case for RCP 8.5, the maximum temperature has been projected to increase by nearly 4 °C and the minimum temperature to overtop 4 °C in 2080s for ACCESS and MPI.

Though, having found a specific trend of change in temperature, precipitation trends are found to be erratic. As KHP–I is a reservoir-based hydropower, it requires the seasonal precipitation and discharge to be analyzed. Hence, Fig. 5 showing the seasonal change in precipitation, projects the precipitation in the wet season to decrease within a range of 0.3–16% in almost all periods and RCMs except an increase of less than 8% in 2080s under RCP 4.5, 2020s and 2050s under RCP 8.5 of MPI. Although the percentage of decrease is projected to be under 20%, it represents the large wet season precipitation having a huge impact on hydropower generation. While the same in the dry season is projected to increase by up to 40% in 2080s of CNRM under RCP 8.5. Moreover, the contribution of 40% represents the low dry season precipitation which is extremely small. Additionally, ACCESS projected the decrease in wet season precipitation to gradually intensify from 2020s towards 2080s from 0.3–7% under RCP 4.5 and 1.5–13% under RCP 8.5. In case of dry season, the maximum increase projected by ACCESS is 14.5% in 2050s under RCP 4.5. Again, under RCP 8.5 gradual increase in precipitation within 7–23.5% from 2020s to 2080s is projected. Further, amongst all RCMs CNRM projected a maximum decrease in wet season precipitation of 15.5% in 2080s under RCP 4.5 and a maximum rise in dry season precipitation of 40% in 2080s under RCP 8.5. Furthermore, a reduction in precipitation due to climate change simultaneously decreases discharge. Also, the performance evaluation results of the linear scaling bias correction method for maximum temperature, minimum temperature, and precipitation have been illustrated in Table S2 of the supplementary table.

3.2. Hydrological analysis

3.2.1. Evaluation of the hydrological model

The hydrological model evaluation process was carried out based on annual, wet season and dry season daily discharge. As reservoir-based hydropower performance is highly sensitive to seasonal flow (Qin et al., 2020), it is important for the model to also simulate the seasonal flow within the acceptable range of statistical indicators in addition to the annual daily discharge. The hydrograph for the calibration and validation of the model is shown in Fig. 6 along with precipitation. The discharge simulated by the model is observed to simulate well following the trend similar to

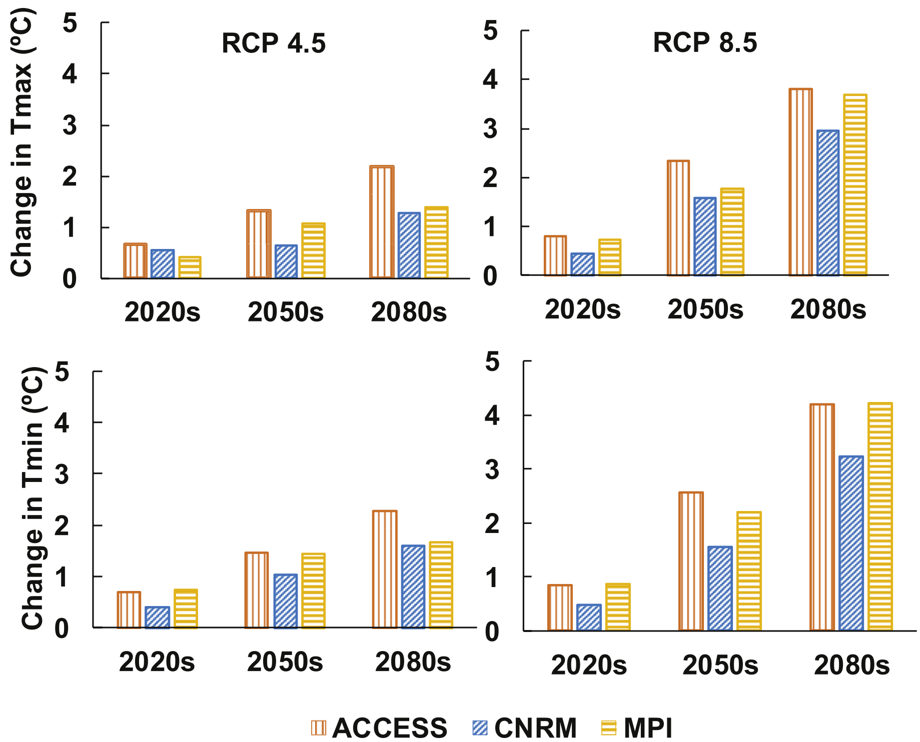

Fig. 4. Change in maximum and minimum temperature for three different periods and RCMs under RCP 4.5 and RCP 8.5 scenario compared to baseline period of 1976–2005 for Daman station.

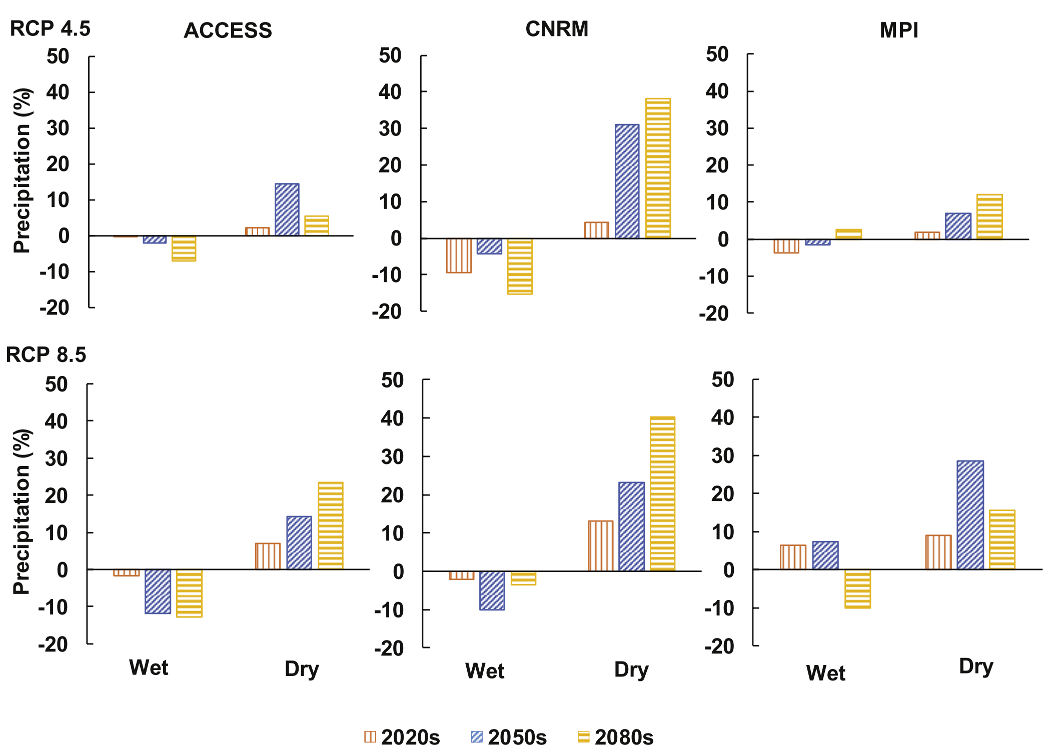

Fig. 5. Seasonal change in precipitation in different periods for three RCMs ACCESS, CNRM and MPI under RCP 4.5 and RCP 8.5 in KRB.

the observed daily discharge. In addition, the peak of the simulated discharge is found to match the time of peak of the precipitation. Further, the results of the calibration and validation of the SWAT model for KRB is presented in Table 2. For annual daily discharge, R^2 is found to be 0.75 and 0.81, NSE is found to be 0.68 and 0.79, and RSR is found to be 0.45 and 0.57 for calibration and validation period respectively. Whereas, the simulation underestimated the volume of water by 16.72% and overestimated the volume of water

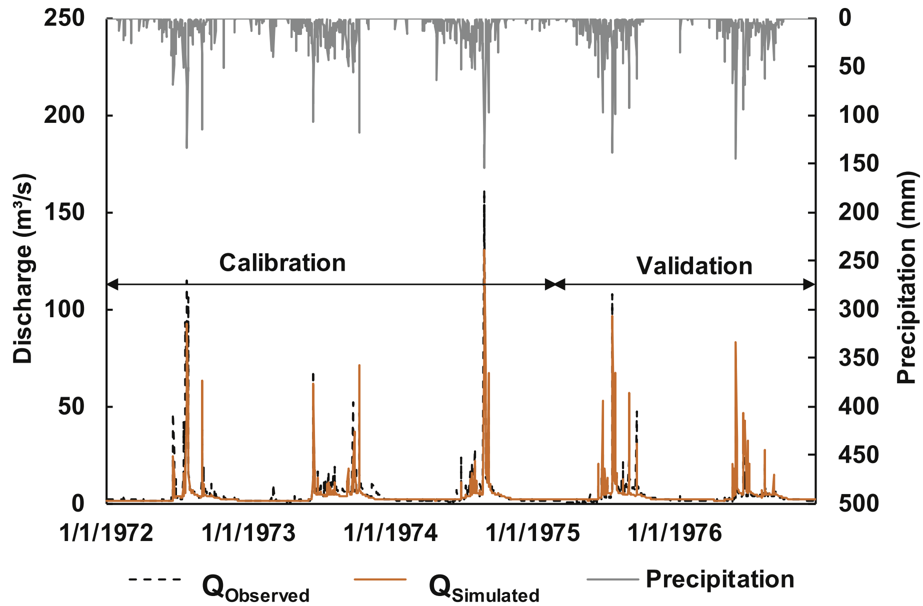

Fig. 6. Comparison of observed and simulated hydrograph during calibration and validation of hydrological model for 1972–1976 of the KRB.

Table 2
Evaluation of hydrological model performance for KRB for the calibration and validation period from 1972 to 1976.

Statistical Indicators	R^2	NSE	PBIAS (%)	RSR
		Annual daily discharge		
Calibration (1972–1974)	0.81	0.79	16.72	0.45
Validation (1975–1976)	0.75	0.68	−13.34	0.57
		Wet season daily discharge		
Calibration (1972–1974)	0.80	0.80	20.30	–
Validation (1975–1976)	0.70	0.60	−10.40	–
		Dry season daily discharge		
Calibration (1972–1974)	0.80	0.70	8.10	–
Validation (1975–1976)	0.80	0.50	−20.50	–

by 13.34% for calibration and validation period respectively. Even though, PBIAS shows underestimation in the calibration period and overestimation during the validation of the discharge it was found within the satisfactory range of ±25%.

Furthermore, based on the seasonal daily discharge R^2 is found to be greater than 0.6, NSE is found to be greater than or equal to 0.5 and PBAIS is found to be within ±21% for both wet and dry season which were within the acceptable range. Therefore, the overall performance of the model is indicated to be satisfactory based on the annual, wet season and dry season daily discharge.

Additionally, the SWAT model performance was further evaluated based on the FDC of the daily discharge using the statistical indicators R^2 and PBIAS. It helped in obtaining a clear idea about the performance of the model at different levels of flow. The results shown in Table S4 of the supplementary table depicts the good performance of the model with R^2 value above 0.8 for every flow regime (Moriasi et al., 2007). Although PBIAS reveals the good performance of the model at high flows and poor performance at low flows, both are still acceptable as this study was not concerned with the low flow. Also, the SWAT model was found to not perform well for low flow (Pradhan et al., 2020). Moreover, the hydropower is mostly concerned with the available high and medium discharge of the river rather than low flow. Fig. 7 illustrates the FDC for the observed and simulated flow for KRB.

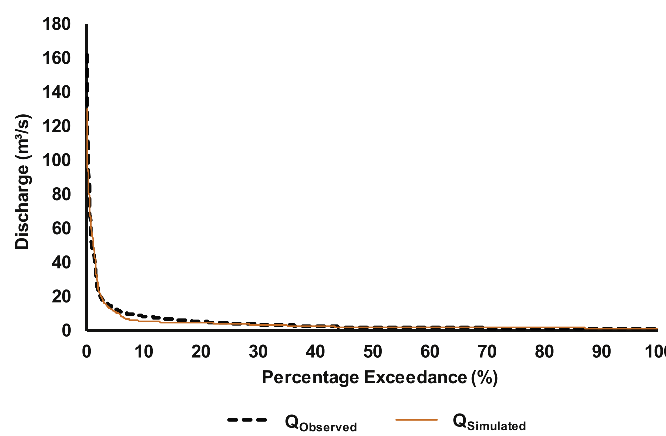

Fig. 7. FDC for the observed and simulated discharge for 1972–1976 of the KRB.

3.2.2. Analysis of climate change impact on future discharge

Fig. 8 depicts the average monthly discharge for 2020s, 2050s, and 2080s compared with the baseline period under RCP 4.5 and RCP 8.5 scenario. It shows high discharge in the wet season from June to September with the peak flow in July. In case of ACCESS, the baseline is observed to be overlapped in almost all periods. Except for the baseline peak discharge of 16 m^3/s in July is projected to decrease around 14 m^3/s in 2020s and 2080s under RCP 4.5. Similarly, the discharge in the month of August is projected to decrease from 13 m^3/s in the baseline period to less than 11 m^3/s in 2080s under RCP 4.5. While for RCP 8.5, the peak discharge is projected to decrease to less than 12 m^3/s in 2050s and 2080s which is found to be less than the baseline discharge of 13 m^3/s in August. Unlike, the ACCESS shift in the time of peak is spotted from July to August in 2020s and 2050s under RCP 4.5 of CNRM. Moreover, the discharge in the month of August is projected to be increased to more than 16 m^3/s in 2050s overtopping the baseline peak discharge, whereas the same in 2080s is projected to drop to 11 m^3/s. In addition, the peak discharge in 2020s and 2080s is projected to be under 13 m^3/s. Likewise, for RCP 8.5, baseline discharge is projected to be

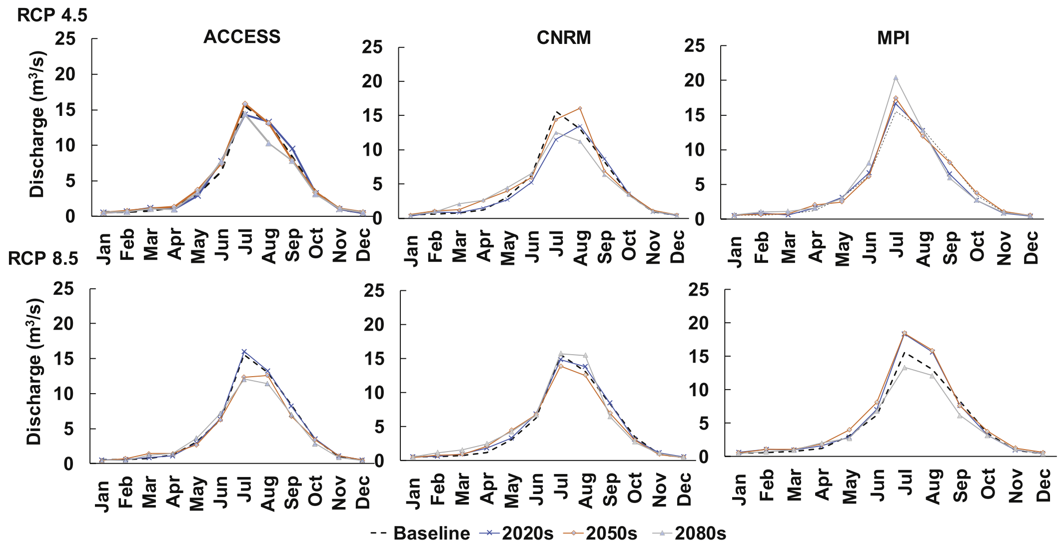

Fig. 8. Future average monthly discharge for 2020s, 2050s and 2080s under RCP 4.5 and RCP 8.5 scenario compared with the baseline period (1976–2005) for KRB.

overlapped by 2020s but 2050s projected July and August discharge to be decreased to 13.8 m^3/s and 12.5 m^3/s from the baseline discharge of 15.5 m^3/s and 13 m^3/s. While 2080s projected it to rise to more than 15 m^3/s for both the months. However, different is the case for MPI where peak baseline discharge of 16 m^3/s is projected to be increased to the range of 17 m^3/s to 21 m^3/s for different periods in July under RCP 4.5. In the like manner, wet month discharge of 2020s and 2050s are projected to be synchronized along with rise of peak discharge to 19 m^3/s under RCP 8.5 In contrast, the discharge in 2080s is projected to be decreased after the onset of the wet season and throughout the wet season compared to the baseline. Finally, most of the RCMs projected a gradual shift in the time of peak from July to August.

In addition, seasonal discharge analysis is carried out for its significance in this research by sectioning it into wet season from June to September and dry season from October to May. The projected change in seasonal discharge is not observed to follow any specific trend but is found to be haphazard for different periods and RCMs under each scenario similar to precipitation. The graph showing the percentage change in seasonal discharge has been presented in Fig. 9.

In case of ACCESS, RCP 4.5 projected the discharge in 2050s to be increased by 2.3% and 10.9% in the wet and dry season respectively. On the contrary, it was projected to be decreased by 11.9% and increased by 4.7% for the same under RCP 8.5. While in the wet season of 2080s it is projected to decrease by 6.5% and 12.7% under RCP 4.5 and RCP 8.5 scenario respectively. Whereas, in case of CNRM, dry season for all periods projected gradual increase in discharge towards 2080s ranging between 2–38% and 8–27% under RCP 4.5 and RCP 8.5 scenario. Moreover, the highest increase of

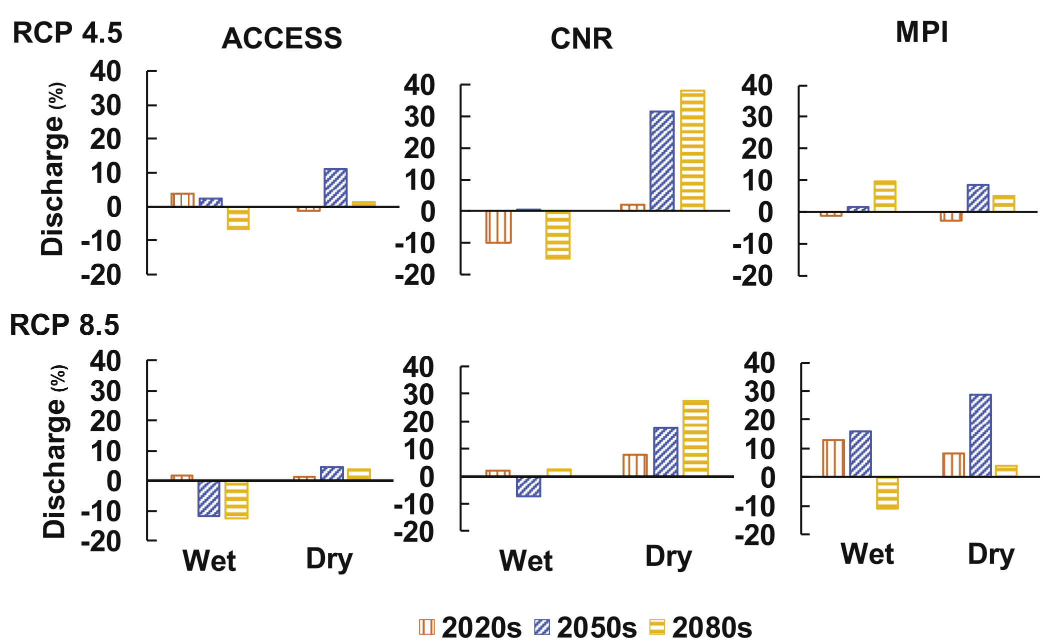

Fig. 9. Seasonal change in the discharge in different periods for three RCMs ACCESS, CNRM and MPI under RCP 4.5 and RCP 8.5 scenario for KRB.

38% in 2080s is projected under RCP 4.5 scenario for dry season amongst all RCMs. Further, in the wet season RCP 4.5 projected decrease in the discharge by 10% and 15% in 2020s and 2080s respectively with no significant changes in 2050s and all periods under RCP 8.5. Besides, MPI projected an increased in discharge of 16% and 28.7% in 2050s in the wet and dry season respectively, under RCP 8.5. Therefore, discharge in the wet season is projected to decrease and the same in the dry season is projected to increase in most of the RCMs. Although the percentage increase in the dry season is projected to be high, it does not have a significant contribution to the hydropower as it attributes to the low discharge of the dry season. Whereas, the decrease in the discharge of the wet season will have a huge impact on the hydropower generation in future.

3.3. Reservoir simulation with HEC- ResSim

3.3.1. Analysis of climate change impact on hydropower generation

Climate change has a significant impact on the reservoir-based hydropower due to its direct impact on the seasonal discharge available in the river on which generation is dependent. For the analysis of the climate change impact on the KHP−I, hydropower generation for the baseline period of 1983−2009 is projected and compared with the future time period of 2020s, 2050s and 2080s. The projected future hydropower generation is compared with the baseline annual generation of 144.3 GWh and presented in Table 3. The percentage change in the generation has been listed with the projection of the maximum decrease of 13.1% in 2080s for ACCESS under RCP 8.5. Additionally, the overall decrease in the generation for all RCMs in different periods under both the scenarios is projected to range from 0.1% to 13.1%. Further, hydropower generation is projected and plotted on a monthly basis in Fig. 10.

In case of RCP 4.5 of ACCESS, monthly projected hydropower generation in the dry season is projected to be same as that of the baseline except for the months near the onset and offset of the wet season. Moreover, in April generation is projected to decrease in all periods with a maximum drop in 2020s by almost 3 GWh. Likewise, May of 2050s and 2080s projected a decline of 1.2 GWh and 2.7 GWh respectively. Conversely, in October of 2020s an increase of more than 1 GWh is anticipated. Whereas it is projected to decrease in most of the months in the wet season in almost all RCMs and periods. The generation in the wet season is projected to decrease with an exceptional increase of only 1 GWh from June to August in 2020s. In contrast, decrease ranging from 1 GWh to 4 GWh with a maximum decrease in September of 2050s and in August and September of 2080s is anticipated. Likewise, for RCP 8.5 scenario significant decrease is projected to range from 1 GWh to 3 GWh from May to October in all periods except for 4 GWh of decrease in September of 2080s.

Further, both the scenarios of CNRM and MPI is anticipated to equal the generation of baseline from October to April, while most of the wet season is projected to decrease. In 2020s of CNRM, the generation is expected to be lesser than the baseline for both the scenarios apart from few months in RCP 4.5 with 10 GWh of generation in August and September including 2 GWh of increased generation in October. Also, for 2050s and 2080s under RCP 4.5 the generation is projected to equal the baseline from dry season until June and eventually drop by almost 2 GWh for the remaining wet season. In 2050s and 2080s, the generation is anticipated to be lower than baseline production with the decrease ranging between 1 GWh and 3 GWh. Lastly, MPI projected a decline in generation for 2020s and 2050s under RCP 4.5 to be under 2 GWh. While 2080s projected a significant decrease in generation of 2.3 GWh only in September. In case of RCP 8.5, the generation in 2080s is projected to drop by about 4 GWh from July to September and other periods projected almost no changes compared to the baseline generation.

3.3.2. Maximization of the hydropower generation with the reservoir rule curve modification

Fig. 11 displays the comparison of different modified rule curves. Additionally, Table 4 lists out modified rule curves with the corresponding annual hydropower generation and percentage difference in generation compared to the baseline annual generation of 144.3 GWh in different periods. A total number of ten different rule curves were chosen depending on the time of peak and shifts in the time of peak of rainfall. The hydropower generation with the modified rule curves are also observed to be decreasing but the range of decrease is found to be within the range of 0.3−11.3%, which is lesser than without modification. The hydropower generation even with the modified rule curves is observed to be still decreasing which signifies the necessity of adapting to different rule curves for different periods as climate change impacts on the hydropower generation in different periods and scenarios are different. In addition, the hydropower generation under the impact of climate change is projected to decrease inevitably in all period compared to the baseline hydropower generation of 144.3 GWh. Therefore, though the impact of climate change on the hydropower generation cannot be eliminated completely it can be reduced to some extent. Based on the annual hydropower generation of the modified rule curves in a particular period compared with the baseline generation, the maximum hydropower generating rule curve is selected for a particular period. Likewise, Rule curve 5 is found to be most suitable for 2020s with an average annual generation of 138.3 GWh and 143.5 GWh for both RCP 4.5 and RCP 8.5 scenario. Besides, it is also found to be suitable for 2080s of RCP 8.5 with an annual average generation of 138 GWh. Whereas, rule curve 6 is found favorable for 2050s and 2080s of RCP 4.5 with an average annual generation of 143.8 GWh and 142.6 GWh respectively. Correspondingly, rule curve 6 is also found suitable for 2050s of RCP 8.5 scenario with an annual average generation of 142.9 GWh. However, climate change impact can be reduced to some extent following the rule curve 5 and 6 for a specified period

Table 3
Projected future hydropower generation compared to the baseline (1976−2005) generation of 144.3 GWh/yr.

RCMs	Scenario	Hydropower Generation (GWh)				Percentage Difference (%)		
		Baseline	2020s	2050s	2080s	2020s	2050s	2080s
ACCESS	RCP 4.5	144.3 GWh/yr	143.6	134.0	129.0	−0.5	−7.1	−10.6
	RCP 8.5		131.9	126.8	125.4	−8.6	−12.1	−13.1
CNRM	RCP 4.5		141.9	139.9	135.4	−1.7	−3.0	−6.2
	RCP 8.5		135.2	133.8	139.4	−6.3	−7.3	−3.4
MPI	RCP 4.5		132.4	133.6	138.8	−8.2	−7.4	−3.8
	RCP 8.5		139.5	144.1	126.9	−3.3	−0.1	−12.1

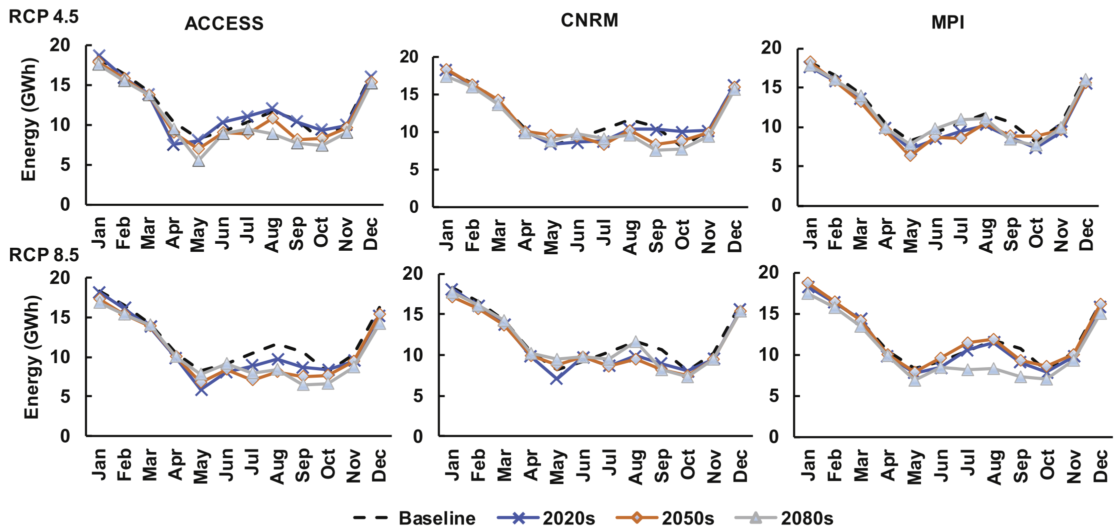

Fig. 10. Monthly projected future hydropower generation of KHP–I for 2020s, 2050s and 2080s under RCP 4.5 and RCP 8.5 scenario compared with the baseline (1982–2009).

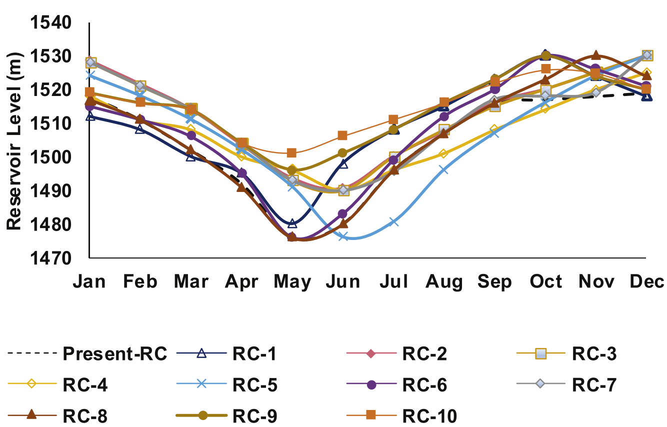

Fig. 11. Comparison of reservoir level for rule curves (RC denotes rule curve).

and increase the generation higher than that of the projected present rule curve to obtain the maximum possible generation under the impact of climate change.

Climate change is an unprecedented and irreversible process and with a huge impact on the hydropower production of KHP–I. Nevertheless, adapting the KHP–I to the future climate can redeem the impacts of climate change. Application of different structural and non-structural measures can help in maximizing the hydropower production while minimizing other constraints. KHP–I is projected to have fluctuation in the amount of inflow to the reservoir and reduction in the wet season discharge eventually leading to fluctuations in hydropower generation. As Kulekhani reservoir performance is highly sensitive to the changes in the seasonal distribution of discharge, it is necessary to adjust the operation and maintenance strategies to fit the changes in climate under different scenarios. Moreover, separate reservoir operation

Table 4
Comparison of hydropower generation by modified rules curves with the baseline (1982–2009) annual generation of 144.3 GWh/yr.

Rule Curve	Scenario	Baseline	Hydropower Generation (GWh)			Percentage Difference (%)		
			2020s	2050s	2080s	2020s	2050s	2080s
Present	RCP 4.5	144.3 GWh/yr	133.9	142.1	141.0	−7.2	−1.5	−2.3
	RCP 8.5		141.1	141.2	136.3	−2.2	−2.1	−5.5
1	RCP 4.5		128.3	133.8	135.1	−11.1	−7.3	−6.4
	RCP 8.5		134.6	134.8	131.3	−6.7	−6.6	−9.0
2	RCP 4.5		137.6	141.9	140.4	−4.6	−1.7	−2.7
	RCP 8.5		142.0	141.6	136.7	−1.6	−1.9	−5.3
3	RCP 4.5		137.4	142.2	140.4	−4.8	−1.5	−2.7
	RCP 8.5		142.1	141.8	136.9	−1.5	−1.7	−5.1
4	RCP 4.5		135.6	140.8	139.6	−6.0	−2.4	−3.3
	RCP 8.5		141.3	140.1	135.7	−2.1	−2.9	−6.0
5	RCP 4.5		138.3	143.3	141.8	−4.2	−0.7	−1.7
	RCP 8.5		143.5	142.5	138.0	−0.6	−1.2	−4.4
6	RCP 4.5		136.2	143.8	142.6	−5.6	−0.3	−1.2
	RCP 8.5		143.4	142.9	137.4	−0.6	−1.0	−4.8
7	RCP 4.5		135.8	141.8	140.4	−5.9	−1.7	−2.7
	RCP 8.5		141.1	140.3	136.2	−2.2	−2.8	−5.6
8	RCP 4.5		134.1	142.1	141.1	−7.1	−1.5	−2.2
	RCP 8.5		141.1	141.3	136.4	−2.2	−2.1	−5.5
9	RCP 4.5		128.0	134.9	133.7	−11.3	−6.5	−7.3
	RCP 8.5		135.3	134.2	130.0	−6.2	−7.0	−9.9
10	RCP 4.5		130.2	133.1	135.4	−9.8	−7.8	−6.2
	RCP 8.5		135.3	134.2	130.0	−6.2	−7.0	−9.9

rule curves must be adopted based on climate change in different periods to optimize hydropower production from minimum to maximum water level. In addition, the unwanted spills can be reduced by capturing the excess water with the construction of smaller reservoirs upstream of the Kulekhani reservoir within the catchment area, decreasing the sediment inflow per year and increasing the height of the dam. Even a small increase in the height of the dam can increase the water storage capacity to a great extent and head gain to increase the generation of hydropower with thesame discharge. Furthermore, changing the land use pattern (vegetation) in the catchment area to increase dry period baseflow and decreasing the reservoir surface evaporation by surface sealing. Also, replacing the turbine with high efficiency so as to increase hydropower production with the same head and discharge.

4. Conclusions

The study was based on the projection of precipitation and temperature and the impact of change in climate on the discharge of the river followed by fluctuations in the hydropower generation. The maximum and minimum temperatures were projected to increase using all three RCMs under both RCP scenarios, i.e. RCP 4.5 and RCP 8.5. The maximum temperature was projected to increase by nearly 4 °C and the minimum temperature was projected to overtop 4 °C under RCP 8.5 of ACCESS and MPI by the end of 2099. Besides, the increase in minimum temperature is expected to be higher than maximum temperature. Further, the precipitation follows no specific trend as opposed to trends of temperature. Instead, the precipitation and discharge are projected to increase in dry season and decrease in the wet season which is an indicator of climate change. The CNRM projected the maximum decrease in wet season precipitation by 15.4% in 2080s and rise in the dry season precipitation by 31% and 38% in 2050s and 2080s under RCP 4.5. Alongside, under RCP 8.5, maximum declination in wet season precipitation was projected by ACCESS in 2050s and 2080s by more than 12% and an increment of 40% in dry season of 2080s of CNRM. Likewise, the ACCESS projected wet season discharge also to decline by more than 12% in 2050s and 2080s under RCP 8.5 whereas CNRM projected 38% increment in discharge in 2080s under RCP 4.5. Furthermore, shift in the time of peak discharge has been observed from July to August for RCP 4.5 of CNRM in 2020s and 2050s, which is expected to disrupt the rule curve-based operation of KHP. Consequently, hydropower production is projected to decrease due to the projected decrease in the discharge with a maximum decrease of 13% in 2080s of ACCESS under RCP 8.5. Furthermore, as KHP–I depend on the seasonal flow, even a slight decrease in the wet season flow has a prominent impact on its dry season hydropower generation. As a result, Kulekhani-II and Kulekhani-III hydropower projects will also have a reduction in its generation as these projects are highly dependent on the regulated outflow from KHP–I. Additionally, the KHP has still been operating under the rule curves developed initially which does not match with the current situation of climate change resulting in fluctuation of discharge in the river. Therefore, modified reservoir rule curves were simulated to maximize the hydropower generation and adapt KHP–I to the projected change in climate. The modification was found to drop the range of decrease in generation within 0.3–11.3%. Hence, it is recommended to adjust rule curves in accordance with the climate change in different period for the smooth operation and production. Similarly, increasing the height of the dam, reducing the annual sediment inflow to the reservoir, utilizing the unwanted spill, changing the land use pattern, reservoir surface sealing for evaporation reduction could further help in the adaptation of KHP–I to climate change. In order to further improve this study, factors such as sedimentation problem and land use change which also significantly impacts hydropower production could be included in further studies. Finally, as KHP is a cascade hydropower project incorporating the downstream projects is highly recommended.

Credit author statement

The first author collected data, conducted modeling experiments. The second author conceptualized the research. All other authors contributed in terms of comments and suggestions to improve the research.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.123483.

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