# Assessment of Climate Change Effects on the Hydrological Regime of Bagmati River Basin using SWAT Model

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ABSTRACT

Developing economies have been particularly vulnerable to the consequences of climate change due to their quickly growing populations and underdeveloped social and economic infrastructure. The Bagmati River Basin (BRB) belonging to such an economy is susceptible to the effects of climate change, including droughts and floods brought upon by changes in discharge. This study assessed the potential effects of climate change on discharge in BRB using the Soil and Water Assessment Tool (SWAT). The model was calibrated and validated based on observed flow data from 2000-2010 at two outlets: Khokana and Padhera Dovan. Using $R^2$, NSE, PBIAS, RSR, and p-factor, the goodness of fit between the final simulated values and the observed values were evaluated. Historical data from three meteorological stations and bias-corrected global climate model (GCM) outputs from the ACCESS-CM2 model were used to drive the calibrated SWAT model under two scenarios (SSP 2-4.5 and SSP 5-8.5) from the IPCC Sixth Assessment Report (AR6). The study demonstrated long-term spatial and temporal variations in hydrologic responses to future climate changes, providing insights for water resources managers and those involved in mitigating natural hazards in the region.

**Keywords**: Climate Change, Bagmati River Basin, GCM, ACCESS-CM2, spatial and temporal variations.

## 1. Introduction

Climate change has significant impacts on various sectors in Nepal, particularly the water resources sector (Lamichhane and Shakya, 2019; WECS and CS, 2011). Studies indicate a strong warming trend of over 6°C over the 21st century and variable rainfall patterns in South Asian countries, including Nepal (Almazroui et al., 2020). These changes have affected river discharge, leading to flooding during the monsoon season and water scarcity during pre and post-monsoon seasons (Sharma and Shakya, 2006). The Bagmati River basin has experienced changes in hydrology, resulting in more intense precipitation events and increased flooding. Similarly, summer droughts are expected to be a major concern in the basin over the years (Dahal et al., 2016). In the case of watersheds, the spatial and temporal heterogeneity of hydrogeologic characteristics within it poses more challenges for water resource management (Strayer et al., 2003; Bloschl and Sivapalan, 1995). Floods, particularly during the monsoon months of July and August, pose significant challenges in Nepal due to heavy precipitation, highly undulated topography with high altitudinal variation, and poor urban planning and design (Devkota and Shakya, 2021). The Bagmati River's carrying capacity is insufficient, as it cannot even cater to $1/5^{th}$ of its peak flow. Due to inadequacy of the channel capacity, new spill channels get formed and it leads to increased flooding (Rastogi et al., 2018). Additionally, the basin also faces annual droughts. Early and accurate long-term discharge forecasting is essential for water resource management, flood control, and infrastructure protection (Seo et al., 2015; Pagano et al., 2014; Grimaldi et al., 2013). Understanding long-term variabilities considering multi-decadal fluctuations in hydro-climatic variables is crucial (Arriagada et al., 2019).

To manage water resources in complex watersheds, distributed and semi-distributed hydrological models like the Soil and Water Assessment Tool (SWAT) are crucial for understanding the effects of climate change on river basin hydrology. SWAT has been widely used for discharge prediction and water conservation globally (Oo et al., 2020; Patel and Srivastava, 2013; Zhang et al., 2010; Spruill et al., 2000). The SWAT model can contribute to hydrological forecasting and overall water resource management. While

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previous studies were dedicated on the simulation of discharge of the 21st century based on climate change scenarios for other regions, such analysis is limited to the Bagmati river basin. Previous studies in the Bagmati basin were focused on quantifying the impacts of climate change on precipitation, water yield, and evapotranspiration (Dahal et al., 2016). Discharge simulation for the basin has been done using scenarios such as Representative Concentration Pathways (RCPs), and Special Report on Emission Scenarios (SRES), but the use of more recently developed Shared Socioeconomic Pathway (SSP) scenarios from the Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report (AR6) are lacking. Therefore, it is essential to quantify and understand climate change in the basin and predict future discharge using the updated scenarios. Information on future discharge related to climate change is vital for the effective planning and management of water resources in the Bagmati River basin.

With this background, this study aims to quantify the future discharge and water balance as a result of climate change for the future period 2024-2100 under the SSP 2-4.5 and SSP 5-8.5 scenarios across the Bagmati River basin using the SWAT model. This will give insight to managers, planners, and policymakers for making sustainable water use and flood and drought risk management.

## 2. Study Area

The Bagmati River basin, which has an area of 3,750 square kilometers up to the Nepal-India border, is located in Nepal's central mountainous region as shown in Figure 1. Our study area starts in Khokana with its position at 27°63N-85°29E and terminates in Padhera Dovan with its position at 27°10'N-85°47'E. The upper watershed, or area upstream of Padhera Dovan, is 2,720 sq. km. and contains Kathmandu and the mountainous region. Lower watershed refers to the area below it, which is the Terai's flat alluvial plain (Dhital and Kayastha, 2013). Its main tributaries are Manohara, Bishnumati, Kulekhani, Kokhajor, Marin, Chandi, Jhanjh and Manusmara (Shrestha and Sthapit, 2015).

The basin's climate ranges from subtropical in the southern lowlands (<1,000 masl), warm temperate at mid-elevation levels, and cold temperate in higher elevations, with mean annual temperatures of 20°C to 30°C. The mean annual temperature is between 10°C and 15°C in the cold temperate climate zone (2,000-2,900 masl) and between 15°C and 20°C in the warm temperate climate zone (1,000–2,000 masl). The yearly precipitation averages 1,800 mm, with the summer months accounting for 80% of the total (Cauchois, 2017).

## 3. Data and Methods

### 3.1. Data requirements

The data and methods used for predicting the discharge in the Bagmati River basin are described in this section. Table 1 presents the data sets, types, properties, and sources along with their resolutions and timeframes. The observed river discharge data was derived using a rating curve of both the hydrological stations. The daily precipitation, temperature, and discharge data were collected from the meteorological and hydrological stations as shown in Figure 2.

The meteorological stations were selected based on data availability. The stations having data for the least timeframe, and those having a higher number of missing data were discarded to minimize any errors that could be generated by the model.

### 3.2. Software requirements

The following software were utilized for this study:

#### 3.2.1. ArcSWAT

SWAT is an open-source model that uses GIS data to simulate the spatial variation and hydrological response of a basin, including river discharge, evapotranspiration, percolation, lateral flow, and groundwater flow. It assesses soil health, water quality, and basin management. QSWAT and ArcSWAT are the QGIS and ArcGIS interfaces, respectively. ArcSWAT is a FORTRAN-based graphical user interface within ArcGIS, enabling the manipulation, analysis, and visualization of geospatial data (Ridwansyah et al., 2014). It supports large and complex catchments, predicting the effects of land use and management on water flow, sedimentation, and chemical composition. ArcSWAT streamlines GIS processes specific to hydrologic modeling and facilitates data exchange and editing. It follows a four-step process: watershed delineation, HRU analysis, SWAT input writing and editing, and SWAT simulation.

#### 3.2.2. SWAT-CUP

SWAT-CUP (Calibration and Uncertainty Program) is an independent SWAT model calibration tool. Model calibration is a challenging and rigorous procedure (Vanrolleghem et al., 2003). The reduction of uncertainty resulting from changes in model parameters and structure requires the use of Sensitivity Analysis (SA) and Uncertainty Analysis (UA) (Srivastava et al., 2013; Gupta et al., 2006; Wagener and Gupta, 2005). Markov Chain Monte Carlo (MCMC) method (Vrugt et al., 2008), Parameter Solution (ParaSol), and Sequential Uncertainty Fitting (SUFI-2) (Abbaspour et al., 2004), have recently been developed as calibration and uncertainty analysis techniques for watershed models. These techniques have been linked to the

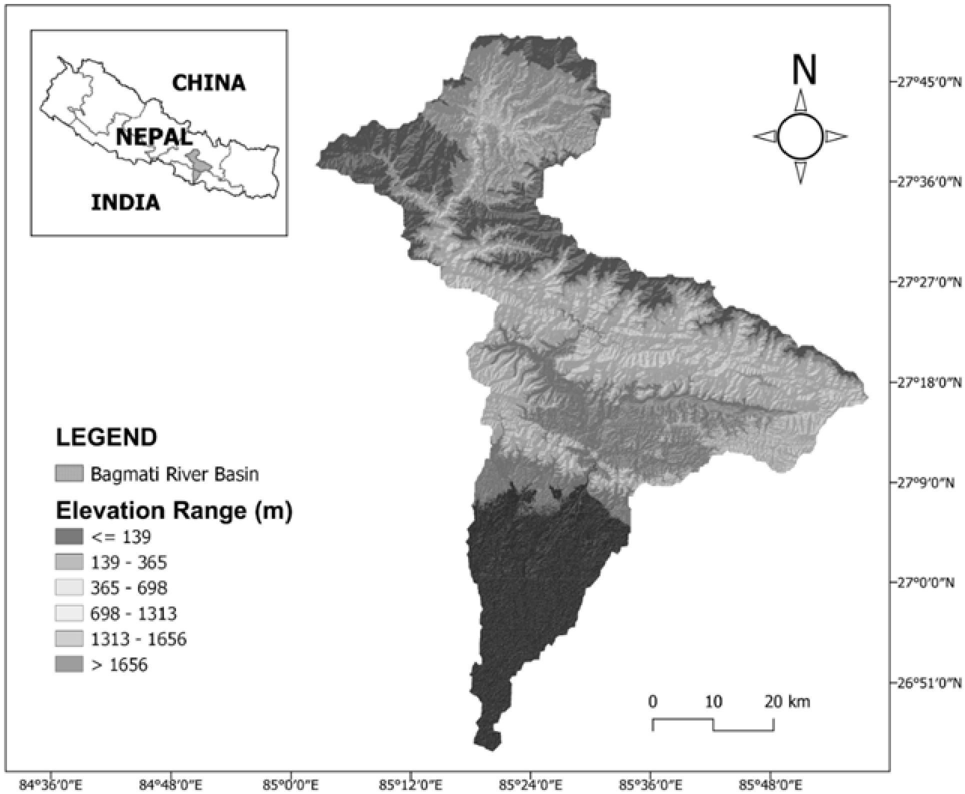


FIG. 1. Location map of the study area, Bagmati River Basin. The inset map shows the location of the Bagmati River basin in Nepal.

SWAT model through the SWAT-CUP algorithm to enable the SA and UA of the model (Rostamian et al., 2008).

### 3.2.3. ArcGIS

ArcGIS by Esri facilitates the analysis and organization of geographic information through layer-based maps. It provides GIS tools for spatial analysis, geo-processing, geometry, and data management. ArcGIS offers reliable solutions for education, nonprofits, and small businesses. It is used in research and the sharing of geographic information online. The software serves as a platform for connecting, exchanging, and analyzing geographic data within organizations.

## 3.3. Methods

The conceptual framework of the methodology for discharge simulation using the SWAT model is shown in Figure 3.

### 3.3.1. Statistical Approaches for Model Performance Evaluation

Model performance was evaluated with Nash-Sutcliffe efficiency (NSE), coefficient of determination ($R^2$), percent bias (PBIAS), p-factor, and the ratio of the root mean square error to the standard deviation of measured data (RSR). The range of statistics for a good model for monthly simulation are PBIAS value within ±15% and NSE and $R^2$ above 0.75 (Moriasi et al., 2007). Thus, the calibration process was done until NSE > 0.75, $R^2$ > 0.75, RSR 0.6, and PBIAS < 15%. The validation process was then performed to check the accuracy of the model for a different dataset.

# 4. Results and Discussion

## 4.1. Model Calibration, Validation, and Sensitivity Analysis

A warm-up period from 1997 to 1999 was designated to initialize hydrological parameters, and the model was simulated daily basis for the years from 2000 to 2010 using the input data series: daily precipitation and daily maximum and minimum temperatures from 1997 to 2010. The

Table 1. Data required for the discharge prediction in the basin.

| Data set (Unit) | Data type | Data description/Properties | Data Source | Resolution/Time Frame |
|---|---|---|---|---|
| Terrain (m) | Spatial Grids | Digital Elevation Model (DEM) | USGS Earth Explorer | 30m X 30m grids |
| Stream (m) | Spatial Vectors | Stream networks and its physical properties | Generated from DEM | |
| Precipitation (mm) | Time-Series | Daily precipitation data from 3 meteorological stations | Nepal DHM[1], ACCESS[2] | (1997-2010) 0.25°(2024-2100) |
| Temperature (°C) | Time-Series | Daily maximum and minimum values from 3 meteorological stations | DHM[1], Nepal, ACCESS[2] | (1997-2010) 0.25°(2024-2100) |
| River discharge ($m^3/s$) | Time-Series | Daily-observed discharge values from 2 hydrological stations | DHM[1], Nepal | (1987-2017) |
| LULC data | Spatial grids | Land-use type(s) covered by different areas | ICIMOD-RDS[3] | 30m X 30m grids |
| Soil data | Spatial grids | Soil textural, physico-chemical properties | FAO[4]/UNESCO[5] | 30m X 30m grids |

[1] Department of Hydrology and Meteorology.
[2] Australian Community Climate and Earth-System Simulator.
[3] Regional Database System.
[4] Food and Agricultural Organization.
[5] United Nations Educational, Scientific and Cultural Organization.

Table 2. List of stations for data collection.

| S.N. | Station name | Index no. | District | Latitude | Longitude | Elevation (m) |
|---|---|---|---|---|---|---|
| I. Meteorological stations | | | | | | |
| 1 | Kathmandu Airport | 1030 | Kathmandu | 27°42'N | 85°22'E | 1337 |
| 2 | Nagarkot | 1043 | Bhaktapur | 27°42'N | 85°31'E | 2147 |
| 3 | Karmaiya | 1121 | Sarlahi | 27°07'N | 85°28'E | 139 |
| II. Hydrological stations | | | | | | |
| 1 | Khokana | 505.05 | Lalitpur | 27°63'N | 85°29'E | 1255 |
| 2 | Padhera Dovan | 589 | Rautahat | 27°10'N | 85°47'E | 180 |

choice of the study period was based on the availability of input data. Daily discharge data from the Khokana and Padhera Dovan stations in the Upper Bagmati River basin and Lower Bagmati River basin, respectively, were used for model calibration, validation, and sensitivity analysis. The period of 2000 to 2005 was selected for calibration, while 2006 to 2010 was selected for validation. Sequential Uncertainty Fitting Algorithm (SUFI-2) of SWAT-CUP was employed for monthly calibration since it requires the least amount of model simulations to produce high-quality calibration and uncertainty data (Yang et al., 2008)).

A total of 22 hydrological model parameters were adjusted to achieve the best fit between simulated and observed discharges. Sensitivity analysis used initial dummy values to identify the most sensitive parameters. The available water storage capacity of the soil layer ($SOL\_AWC$) (t=5.56, p=0.00) in the main channel was the most sensitive parameter. Other sensitive parameters included Soil Conservation Service Curve Number (SCS-CN) at moisture condition II (CN2) (t=3.72, p=0.00), saturated hydraulic conductivity of the soil layer ($SOL\_K$) (t=3.32, p=0.00), revap coefficient ($GW\_REVAP$) (t=2.27, p=0.02), and delay time for aquifer recharge ($GW\_DELAY$) (t=-2.18, p=0.03). Parameters ranked as least sensitive included Manning's 'n' value for the main channel ($CH\_N2$) (t=-1.42, p=0.15), soil evaporation compensation factor ESCO (t=-1.25, p=0.21), and precipitation lapse rate ($ALPHA\_BNK$) (t=-1.22, p=0.22). These parameters play a significant role in representing discharge, channel routing, and evapotranspiration losses in the river basin.

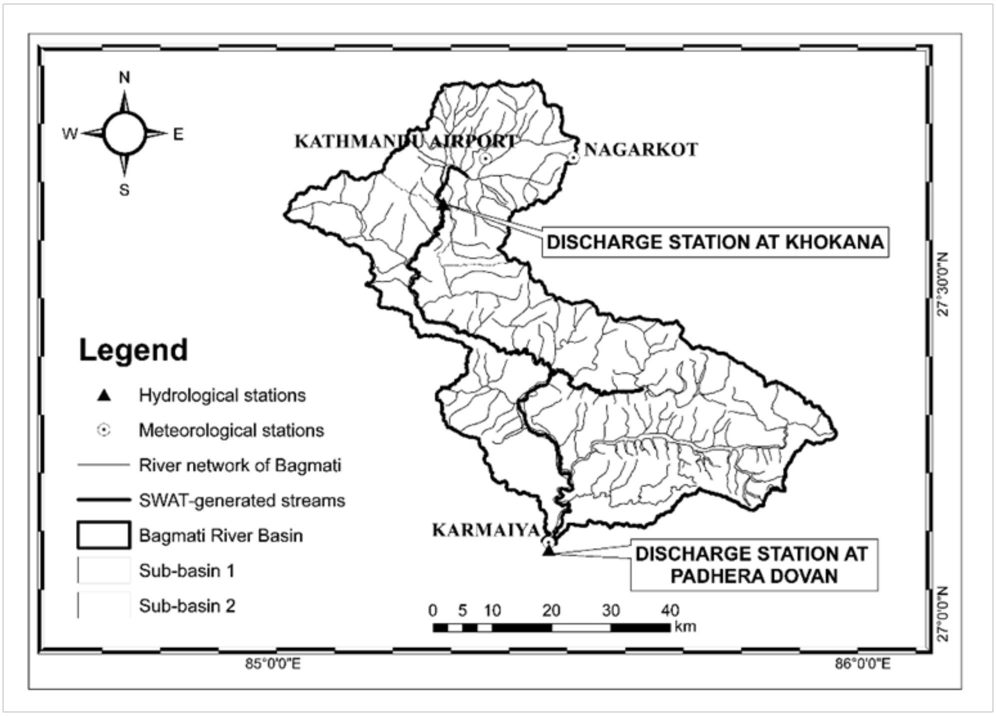


Fig. 2. Locations of meteorological and hydrological stations in the Bagmati River basin used in the study.

Daily simulations of the discharge of Bagmati River at Khokana and Padhera Dovan for the model calibration were carried out from 2000 to 2005 and for the model validation were carried out from 2006 to 2010. Figure 4 shows the calibration and validation curve for the Khokana outlet and Figure 5 shows the calibration and validation curve for the Padhera Dovan outlet.

It can be seen that the time of maximum precipitation also corresponded to the time of peak flow throughout the period. For Khokana, when the $R^2$, NSE and PBIAS values improved to 0.77, 0.74, and 3.7, respectively while decreasing the value of RSR to 0.51, the simulation was seen to be better. The positive PBIAS indicated that simulated discharges are underestimated. Similarly, for Padhera Dovan, when the $R^2$, NSE, and PBIAS values improved to 0.75, 0.75, and -3.5, respectively while decreasing the value of RSR to 0.50, simulation here also was seen to be better.

Better model performance results were obtained during calibration periods. For Khokana station, the values of statistical indicators: $R^2$, NSE, PBIAS, and RSR are all satisfied with the values of 0.77, 0.74, 3.7, and 0.51. For the Padhera Dovan station, the values of statistical indicators: $R^2$, NSE, PBIAS, and RSR were all satisfied with the values of 0.75, 0.75, -3.5, and 0.50, respectively.

Statistical parameters for both calibration and validation periods were satisfactory. $R^2$ values of 0.75 and 0.77 indicated good agreement between simulated and observed discharge. The NSE values for Khokana were 0.74 and 0.67 during calibration and validation, respectively, while for Padhera Dovan, they were 0.75 and 0.75. PBIAS values fell within the specified limitations of 3.7% to -3.5% during calibration and 5.6% to 1.7% during validation. Positive PBIAS indicated underestimation of simulated discharge, while negative values indicated overestimation. RSR values also met acceptable limits. Overall, these results indicated reasonable agreement between simulated and observed discharge, demonstrating acceptable model performance. The validation outcome suggested that the model, with calibrated basin parameters, can reliably simulate future discharge and produce accurate results using projected data. In some years, however, the data used for simulation could be unable to fully capture the variability of monsoon events over a longer period as some of the discharges during monsoon seem to be underestimated by this model. Monsoon seasons can exhibit significant inter-annual variability, and the limited calibration period of only six years in this case might not fully represent all potential monsoon scenarios. Another reason for the underestimation of discharge during the monsoon season could be a limitation of the SWAT model itself in capturing the intensity and magnitude of monsoon rainfall.

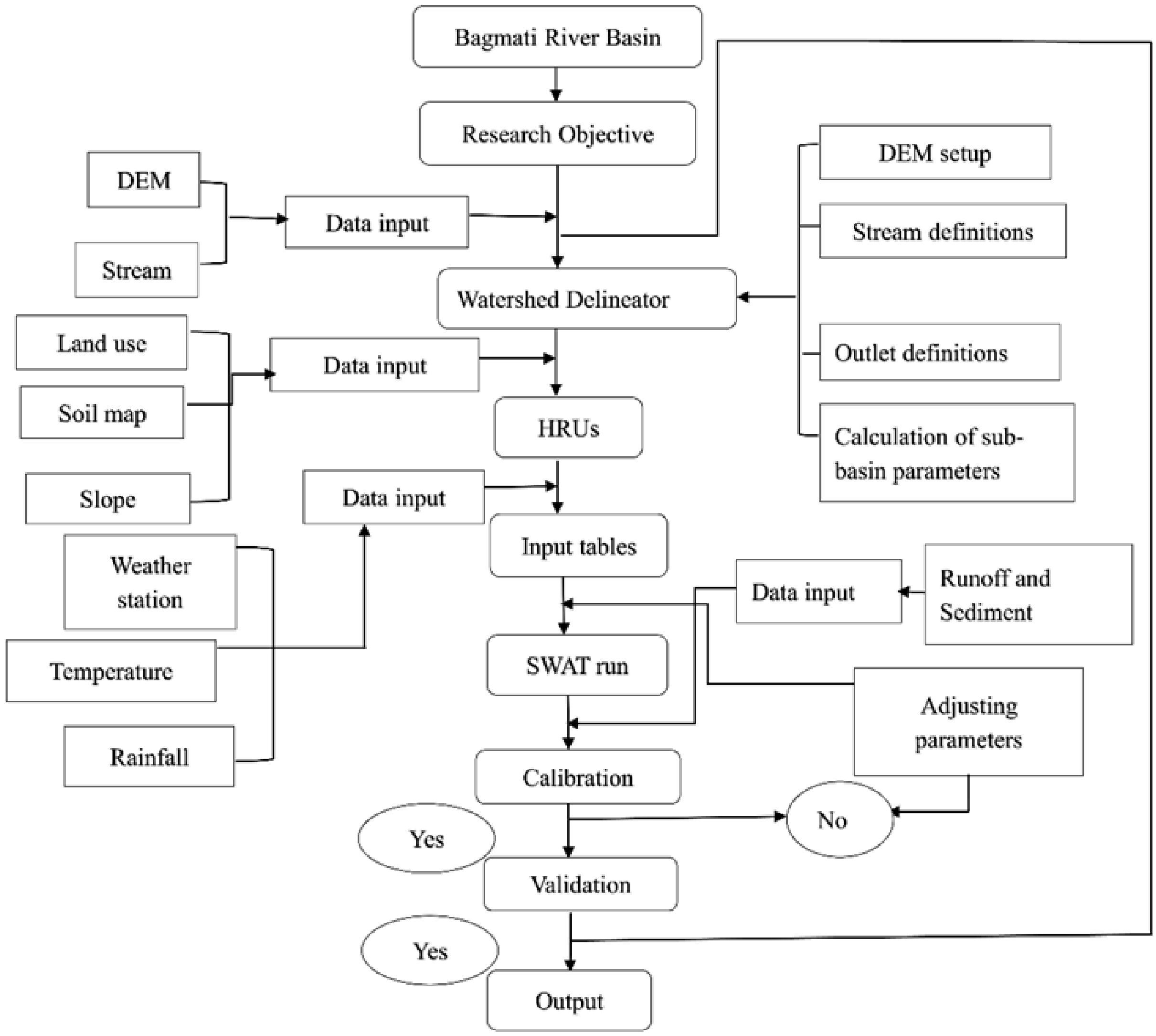


FIG. 3. Conceptual framework of the methodology for discharge simulation using the SWAT model.

## 4.2. Comparison of historical observed discharge with simulated future discharges

The calibrated and validated model was employed to generate future discharges at both stations under the SSP 2-4.5 and SSP 5-8.5 scenarios for the overall 21st century. These scenarios combine Shared Socioeconomic Pathways (SSP) with target radiative forcing levels at the end of the 21st century, representing different socioeconomic and climate futures. Bias-corrected climate projections of daily precipitation, maximum and minimum temperatures at 0.25° spatial resolution for South Asia (India, Pakistan, Bangladesh, Nepal, Bhutan, and Sri Lanka) derived from Coupled Model Intercomparison Project-6 (CMIP-6) by Mishra et al. (2020) was used.

Mishra et al. (2020) conducted bias-corrected projections for South Asia, including countries like India, Pakistan, Bangladesh, Nepal, Bhutan, and Sri Lanka, as well as the 18 Indian sub-continental river basins. The researchers utilized observed daily gridded precipitation, minimum and maximum temperatures from the period of 1951 to 2018. Precipitation data at a resolution of 0.25° were obtained from the India Meteorological Department (IMD) for the Indian region, while gridded precipitation and temperature data for regions outside India were obtained. The gridded datasets were used for bias correction of projec-

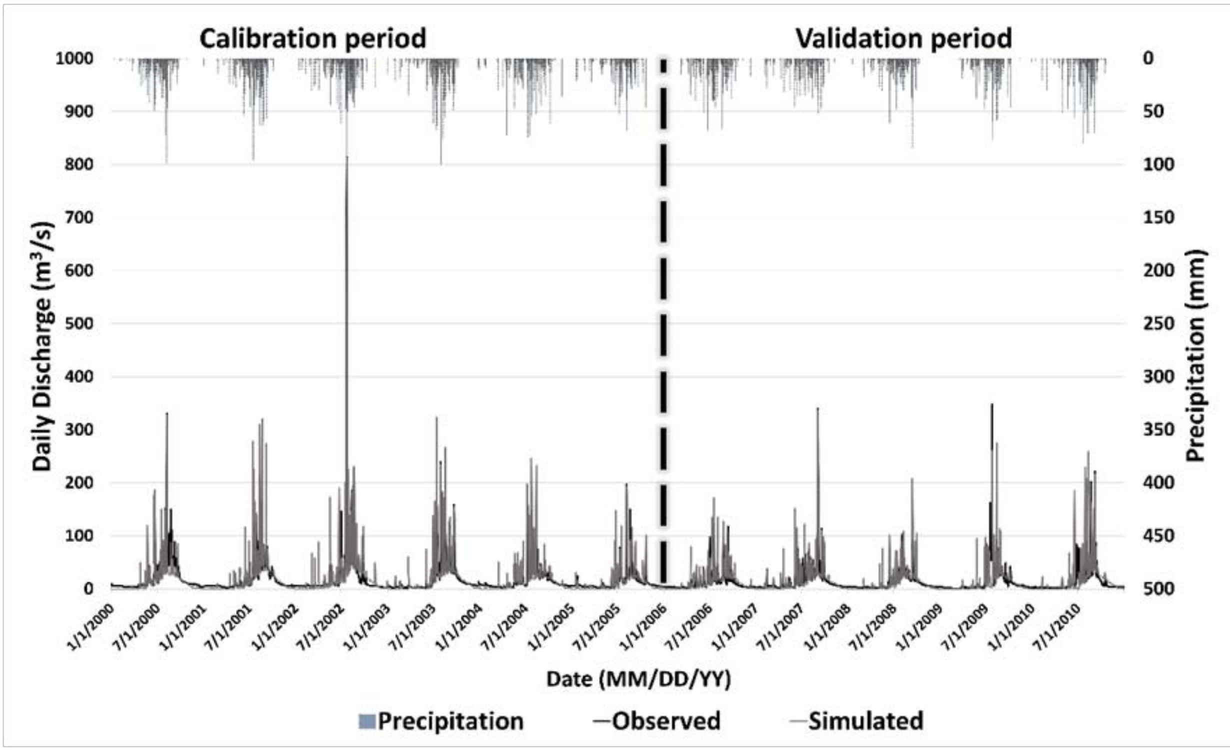


FIG. 4. Observed and simulated discharges and daily precipitation in the Khokana outlet for the calibration period (2000-2005) and validation period (2006-2010).

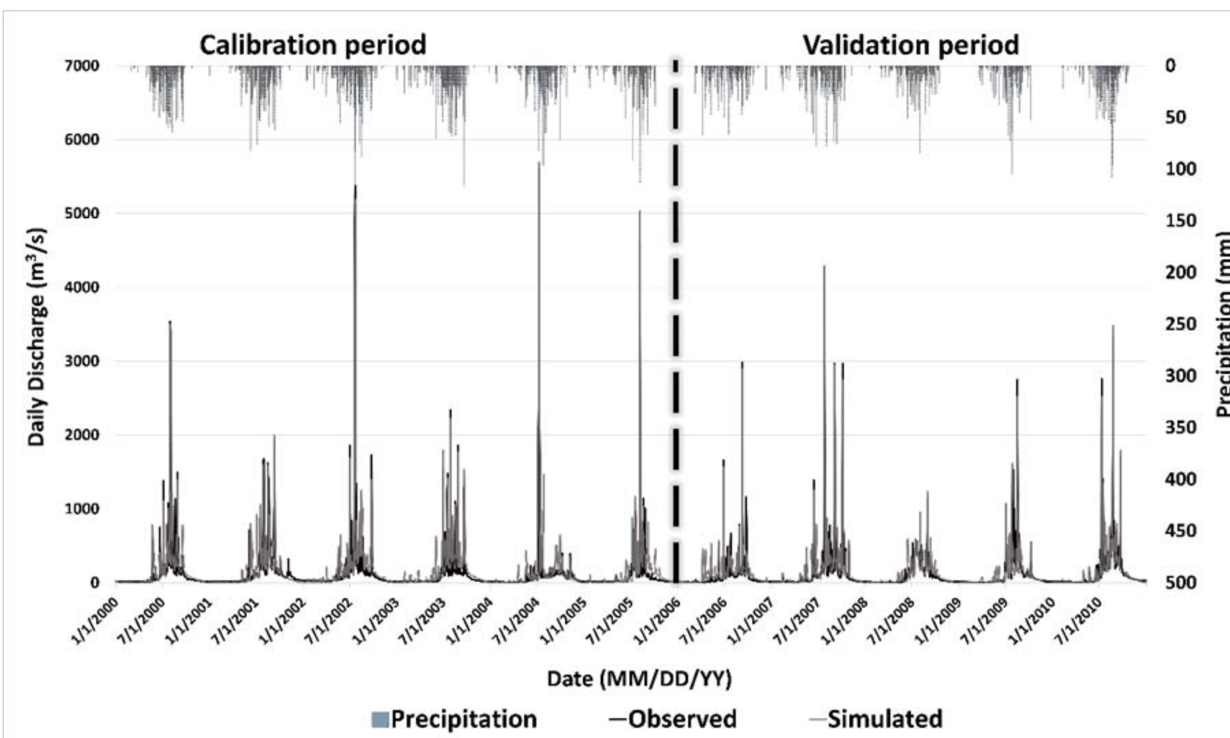


FIG. 5. Observed and simulated discharges and daily precipitation in the Padhera Dovan outlet for the calibration period (2000-2005) and validation period (2006-2010).

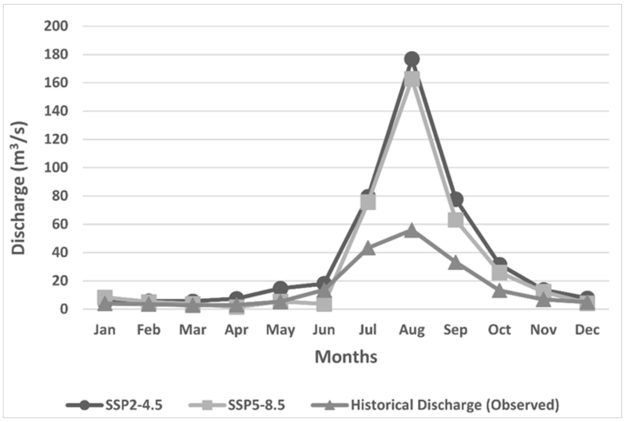


Fig. 6. Comparison of monthly average historical discharge with monthly average future discharge (near future, 2024-2050) under SSP 2-4.5 and SSP 5-8.5 in Khokana outlet.

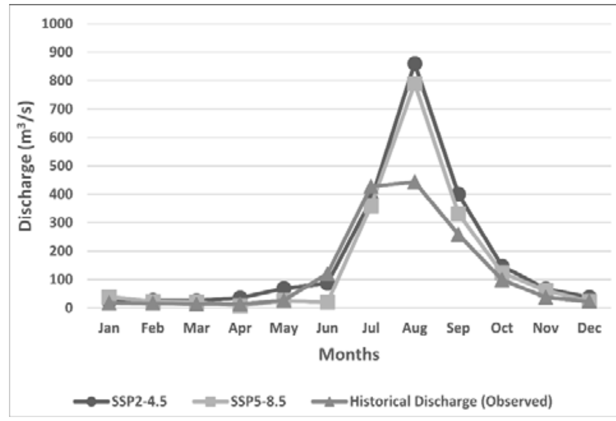


Fig. 7. Comparison of monthly historical discharge with monthly future discharge (near future; 2024-2050) under SSP 2-4.5 and SSP 5-8.5 in the Padhera Dovan outlet.

tions from the CMIP6 models (Pai et al., 2014). Thirteen CMIP-6 global climate models (GCMs) were used, and data for precipitation, maximum and minimum temperatures were available for the historical period (1850-2014) and the future scenarios known as SSP 1-2.6, SSP 2-4.5, SSP 3-7.0, and SSP 5-8.5 (2015-2100). The spatial resolution of the CMIP-6 projections varied among the models, ranging from 0.7° to more than 2° (Gidden et al., 2019; Eyring et al., 2016). Out of the thirteen models, the study used Australian Community Climate and Earth-System Simulator Version 2 (ACCESS CM2) model.

After the model generated future discharges under both the scenarios for the required timeframe, the average monthly discharges from the months of January to December were computed for three time-frames: near future (2024-2050), future (2051-2075) and far future (2076-2100) and the future discharges were evaluated and compared with the historical observed mean monthly discharge for the baseline period (1992-2017).

#### 4.2.1. Changes in monthly future discharge in the near future (2024-2050)

Future discharge at the Khokana hydrological station, particularly in April, May, and June, is projected to decrease under the SSP 5-8.5 scenario compared to both the SSP 2-4.5 scenario and historically observed discharge. Figure 6 provides a visual comparison of the monthly average historical discharge (baseline) and future discharge under the two scenarios at the Khokana outlet in the near future.

Both scenarios indicate an increasing trend of discharge in July (79.49 $m^3/s$ for SSP 2-4.5; 75.60 $m^3/s$ for SSP 5-8.5), August (176.87 $m^3/s$ for SSP 2-4.5; 162.68 $m^3/s$ for SSP 5-8.5) and September (77.74 $m^3/s$ for SSP 2-4.5; 63.08 $m^3/s$ for SSP 5-8.5) as the historical values for the baseline period were 43.38 $m^3/s$ (July), 55.98 $m^3/s$ (August) and 33.18 $m^3/s$ (September). Thus, the projected peak discharges in the monsoon are very high compared to the historical values, especially due to increased precipitation. Under both future scenarios, the increases coincide at peak values and end with a decreasing trend in discharge post-monsoon in October, November, and December, but still somewhat higher than the historical discharge values. The timing of the monsoon remains similar to the present under both SSP 2-4.5 and SSP 5-8.5.

In the near future, the Padhera Dovan hydrological station shows future discharges similar to the historical discharge (baseline period) from January to July and November to December under both the SSP 2-4.5 and SSP 5-8.5 scenarios. Figure 7 provides a visual comparison of monthly historical discharge and future discharge under the two scenarios at the Padhera Dovan outlet in the near future.

For the months starting from August to September, however, the peak discharge values have been projected to increase drastically. There is an increasing trend in discharge under both scenarios, reaching peak points higher than the historical discharge values of 443.76 $m^3/s$ (August) and 258.93 $m^3/s$ (September). Under SSP 2-4.5, the discharge values in August and September are projected to be 860.73 $m^3/s$ and 400.83 $m^3/s$, while under SSP 5-8.5, they are 790.19 $m^3/s$ and 331.53 $m^3/s$. The timing of the monsoon remains the same as the present scenario for SSP 2-4.5 but with higher intensity. Under SSP 5-8.5, the monsoon has shifted to later months with monsoon starting only after July. However, the peak discharge during monsoon has intensified, which indicates a likelihood of amplified flood events during the monsoon months. The discharge plot shows an increasing trend for those months about high precipitation, indicating that high precipitation influences river discharge.

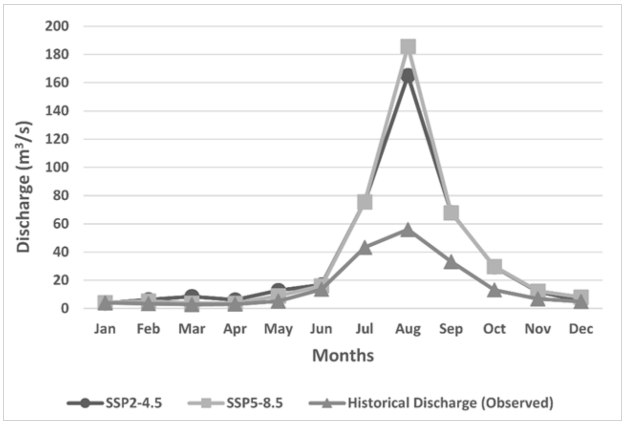


FIG. 8. Comparison of monthly historical discharge with monthly future discharge (future; 2051-2075) under SSP 2-4.5 and SSP 5-8.5 in the Khokana outlet.

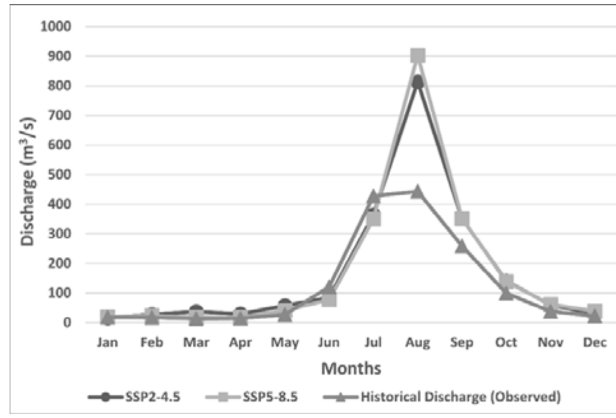


FIG. 9. Comparison of monthly historical discharge with monthly future discharge (future; 2051-2075) under SSP 2-4.5 and SSP 5-8.5 in Padhera Dovan outlet.

#### 4.2.2. Changes in monthly streamflow in the future (2051-2075)

For Khokana hydrological station, the monthly discharge in the future time frame, particularly in July, August, September, and October is seen to be increased significantly with respect to historical observed discharge under both scenarios for which the discharge values are 75.79 $m^3$/s, 165.03 $m^3$/s, 68.11 $m^3$/s, and 29.50 $m^3$/s respectively for SSP 2-4.5 and 75.52 $m^3$/s, 185.77 $m^3$/s, 67.81 $m^3$/s and 29.76 $m^3$/s respectively for SSP 5-8.5. Similar to the results of the Khokana outlet in the near future as obtained in Figure 7, the discharge values of both scenarios are very high in the future monsoon periods compared to the historical discharge which is also related to increased precipitation intensity. The discharge values in future scenarios coincide with each other in most of the months. The only difference is that in the future, the SSP 5-8.5 peak discharge (185.77 $m^3$/s) is expected to be a bit higher than the peak discharge under the SSP 2-4.5 scenario (165.03 $m^3$/s). The timing of monsoons remain the same in the future, however, more flooding events can be expected to occur as well in the future under both scenarios. Figure 8 shows the comparison of monthly historical discharge with monthly future discharge under two scenarios in the Khokana outlet.

For the Padhera Dovan hydrological station, the monthly future discharge in the future time frame, particularly in August and September is seen to be increased with respect to historical discharge under both future scenarios. Under SSP 2-4.5 scenario, the discharge values are projected to be 814.004 $m^3$/s (August) and 351.71 $m^3$/s (September) and under the SSP5-8.5 scenario, the discharge values are 902.7 $m^3$/s (August), 351.82 $m^3$/s (September). These values are relatively high as compared to historical values of 443.76 $m^3$/s (August) and 258.93 $m^3$/s (September). Here too, the discharge values at future scenarios coincides with each other in most of the months, but the peak value in the month of August is slightly higher under SSP 5-8.5. The monthly discharges of both scenarios are related to higher precipitation events. Figure 9 shows the comparison of monthly historical discharge with monthly future discharge under two scenarios in the Padhera Dovan outlet in the future.

The plot is very similar to the one obtained for the near future in Figure 7, implying that discharges are expected to change highly in the distant future as compared to near future. The timing of the monsoon has not changed much as compared to the present scenario, although the severity of the monsoon has changed. In the future, too, severe flooding events are expected to occur under both SSP 2-4.5 and SSP 5-8.5 scenarios.

#### 4.2.3. Changes in monthly future discharge in the far future (2076-2100)

For the Khokana hydrological station, the monthly discharge in the far future time frame, particularly in the monsoon months of July, August, and September is seen to be increased with respect to historical discharge under SSP 2-4.5 scenario for which the discharge values are 65.11 $m^3$/s (July), 177.54 $m^3$/s (August) and 65.29 $m^3$/s (September). Under SSP 5-8.5, the discharge is in the increasing trend starting early from June throughout September with respect to historical discharge, for which the discharge values are 41.26 $m^3$/s (June), 111.85 $m^3$/s (July), 182.77 $m^3$/s (August) and 79.34 $m^3$/s (September).
The discharge values of both scenarios are again very high compared to the historical discharge values of 13.61 $m^3$/s (June), 43.38 $m^3$/s (July), 55.98 $m^3$/s (August), 33.18 $m^3$/s (September), which is related to increased precipitation intensity in the future monsoon periods. The monsoon period has shifted noticeably under SSP 5-8.5, as monsoon

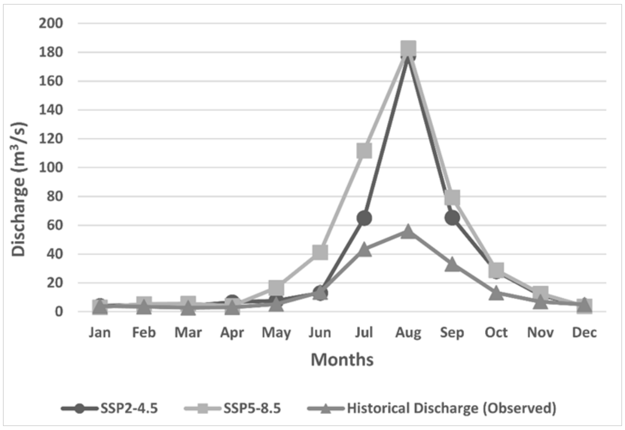


Fig. 10. Comparison of monthly historical discharge with monthly future discharge (far future; 2076-2100) under SSP 2-4.5 and SSP 5-8.5 in Khokana outlet.

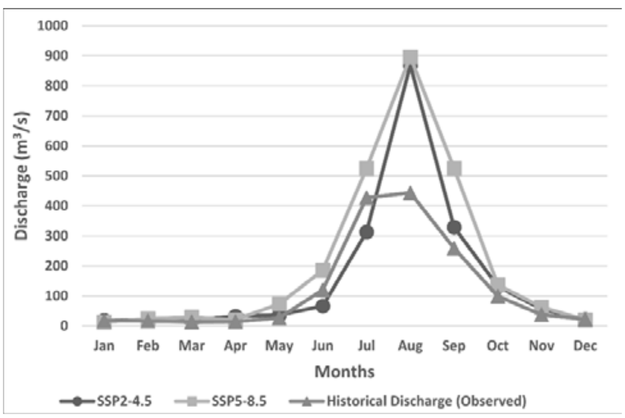


Fig. 11. Comparison of monthly historical discharge with monthly future discharge (far future; 2076-2100) under SSP 2-4.5 and SSP 5-8.5 in Padhera Dovan outlet.

can be expected to start earlier between May and June. Figure 10 shows the comparison of monthly historical discharge with monthly future discharge under two scenarios in the Khokana outlet in the far future.

For the Padhera Dovan hydrological station, the monthly discharge in the future time frame, particularly in August and September is seen to be increased with respect to historical discharge under SSP 2-4.5 scenario for which the discharge values are 868.78 $m^3/s$ (August) and 329.22 $m^3/s$ (September) respectively. Similarly, it is in the increasing trend under SSP 5-8.5 scenario for July, August, and September for which the discharge values are 524.74 $m^3/s$, 897.012 $m^3/s$, and 524.74 $m^3/s$. These values under both scenarios are very high as compared to historical discharge values of 424.74 $m^3/s$ (July), 443.76 $m^3/s$ (August), and 258.93 $m^3/s$ (September). Under SSP 2-4.5, the monsoon is expected to start later in June although this is not a noticeable shift. Under SSP 5-8.5, the monsoon is expected to start early (from mid-May) and last longer (till the last of September), Thus, it can be observed that the timing of monsoon under both scenarios has slightly changed. Figure 11 shows the comparison of monthly historical discharge with monthly future discharge under two scenarios in the Padhera Dovan outlet in the far future.

Overall, the peak discharge is found to be higher under the SSP 5-8.5 scenarios for all future time frames, followed by SSP 2-4.5, than the historical discharge (baseline period). The higher peak discharges in SSP 5-8.5 and SSP 2-4.5 during monsoon months are due to a higher amount of precipitation. This consequently makes us expect high chances of flooding events to occur in the 21st century.

### 4.3. Changes in maximum and minimum discharges in the two outlets

#### 4.3.1. Changes in minimum discharges

For the Khokana outlet, the percentage change in average minimum discharge compared to the baseline scenario (1992-2017) shows a decreasing trend in the near future, future, and far future under both the SSP 2-4.5 and SSP 5-8.5 scenarios. Under SSP 2-4.5, the percentage changes are -847% (near future), -11% (future), and -35% (far future). Under SSP 5-8.5, the percentage changes are -1793% (near future), -6% (future), and -37% (far future). The minimum discharge in the Khokana outlet during dry season comparatively has a higher number of low flow than high flow for both SSP 2-4.5 and SSP 5-8.5 scenarios as shown in Figure 12a.

For the Padhera Dovan outlet, the percentage change in average minimum discharge shows an increasing trend in the near future (2026%) and a decreasing trend in the future (-23%) and far future (-48%) under the SSP 2-4.5 scenario. Under SSP 5-8.5, the percentage changes are -31% (near future), -32% (future), and -37% (far future). Similar to Khokana, the minimum discharge in Padhera Dovan outlet during drier seasons comparatively has a higher number of low discharges than high discharges for both SSP 2-4.5 and SSP 5-8.5 scenarios as shown in Figure 12b. The results suggest that both the outlets and neighboring areas have a high probability of facing water scarcity under the given future scenarios, especially during the dry seasons.

#### 4.3.2. Changes in maximum discharges

For the Khokana outlet, the percentage change in average maximum discharge compared to the baseline scenario (2000-2010) shows a decreasing trend in the near future, future, and far future under both the SSP 2-4.5 and SSP 5-8.5 scenarios. Under SSP 2-4.5, the percentage changes are -15,514% (near future), 139% (future), and 149% (far

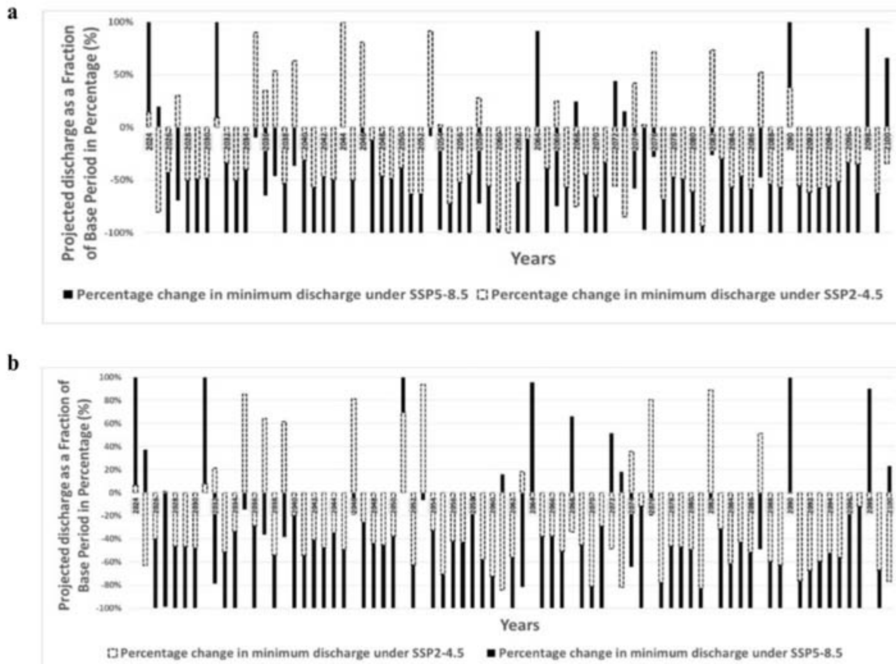


FIG. 12. Trends of minimum discharge under SSP 2-4.5 and SSP 5-8.5 in a) Khokana outlet; b) Padhera Dovan outlet.

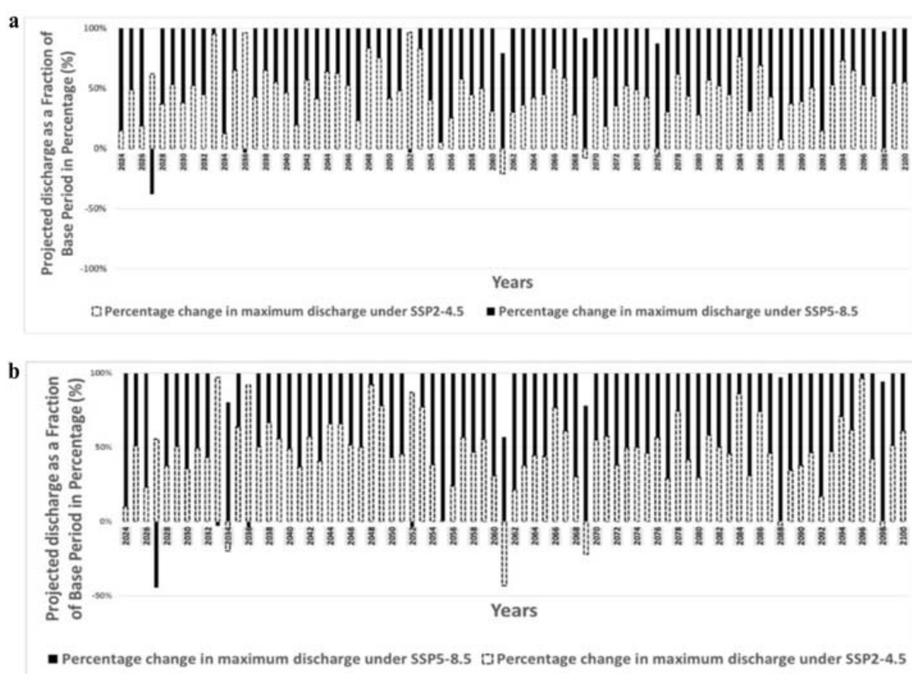


FIG. 13. Trends of maximum discharge under SSP 2-4.5 and SSP 5-8.5 in: a) Khokana outlet; b) Padhera Dovan outlet.

future). Under SSP 5-8.5, the percentage changes are -13,666% (near future), 176% (future), and 197% (far future). The maximum discharge in the Khokana outlet during the monsoon season comparatively has a higher number

TABLE 3. Water balance ratios for historical timeframe.

| Water balance components | Ratios |
|---|---|
| Streamflow/Precipitation | 0.76 |
| Baseflow/Total flow | 0.49 |
| Surface runoff/Total flow | 0.51 |
| Percolation/Precipitation | 0.21 |
| Deep recharge/Precipitation | 0.01 |
| ET/Precipitation | 0.16 |

TABLE 4. Water balance ratios for SSP 2-4.5 scenario.

| Water balance components | Ratios |
|---|---|
| Streamflow/Precipitation | 0.81 |
| Baseflow/Total flow | 0.46 |
| Surface runoff/Total flow | 0.54 |
| Percolation/Precipitation | 0.22 |
| Deep recharge/Precipitation | 0.01 |
| ET/Precipitation | 0.16 |

TABLE 5. Water balance ratios for SSP 5-8.5 scenario.

| Water balance components | Ratios |
|---|---|
| Streamflow/Precipitation | 0.82 |
| Baseflow/Total flow | 0.44 |
| Surface runoff/Total flow | 0.56 |
| Percolation/Precipitation | 0.21 |
| Deep recharge/Precipitation | 0.01 |
| ET/Precipitation | 0.15 |

of high flow than low flow for both SSP 2-4.5 and SSP 5-8.5 scenarios as shown in Figure 13a.
For the Padhera Dovan outlet, the percentage change in average maximum discharge shows an increasing trend in the near future (109%), future (102%), and far future (109%) under the SSP 2-4.5 scenario. Under SSP 5-8.5, the percentage changes are 96% (near future), 119% (future), and 130% (far future). Similar to Khokana, the maximum discharge in the Padhera Dovan outlet during the monsoon months comparatively has a higher number of high discharge than low discharge for both SSP 2-4.5 and SSP 5-8.5 scenarios as shown in the Figure 13b. The results suggest that both the outlets and neighboring areas have a high probability of facing extreme water events including flooding under the given future scenarios, especially during the monsoon months.

### 4.4. Water balance in Bagmati River Basin

The water balance of the Bagmati River basin is studied using the following equation:

$$SW_t = SW_o + \sum R_{\text{day}} - Q_{\text{surf}} - E_a - W_{\text{seep}} - Q_{gw} \quad (1)$$

where
$SW_t$ = final soil water content in mm,
$SW_o$ = the initial soil water content in mm,
$R_day$ = the amount of precipitation in a day in mm,
$Q_surf$ = the amount of surface runoff in a day in mm,
$E_a$ = the amount of evapotranspiration in the day in mm,
$W_seep$ = the amount of water entering the vadose zone in a day in mm and
$Q_gw$ = the amount of return flow in the day in mm.

Under the historical timeframe (2000-2010), SSP 2-4.5 and SSP 5-8.5 scenarios for 2024 to 2100, ratios of water balance components are shown in Tables 3, 4, and 5.

The increasing trend in the streamflow/precipitation ratio suggests that a larger proportion of precipitation is being converted into streamflow in future scenarios compared to the historical timeframe. This could be due to changes in hydrological conditions, land use, or climate patterns. The baseflow/total flow ratio represents the proportion of streamflow that is derived from groundwater sources (baseflow) compared to the total streamflow. The consistent ratio suggests that groundwater contribution to streamflow remains relatively constant across the different timeframes and scenarios. The increasing trend in the surface runoff/total flow ratio indicates that a larger proportion of total flow comes from surface runoff (e.g., rainfall directly flowing into streams) in future scenarios compared to the historical timeframe. This could be attributed to changes in precipitation patterns, land cover, or hydrological processes. The percolation/precipitation ratio represents the proportion of precipitation that infiltrates the soil and recharges groundwater compared to the total precipitation. The constant ratio suggests that the percolation process remains relatively unchanged across the different timeframes and scenarios. The deep recharge/precipitation ratio represents the proportion of precipitation that replenishes deep groundwater reservoirs compared to the total precipitation. The constant ratio indicates that the contribution of deep recharge to the overall water balance remains consistent over time. The ET/precipitation ratio represents the proportion of precipitation that is consumed by evapotranspiration (evaporation from surfaces and transpiration from plants) compared to the total precipitation. The consistent ratio suggests that the overall water loss through evapotranspiration remains relatively constant across the different timeframes and scenarios.

In summary, the results indicate potential changes in the streamflow/precipitation and surface runoff/total flow ratios, suggesting alterations in the hydrological cycle. However, the ratios for percolation, deep recharge, and ET/precipitation remain relatively constant throughout the different timeframes and scenarios. These findings can provide insights into how future water balance components may vary and assist in understanding potential shifts in water availability and usage.

## 5. Conclusion

The study utilized daily discharge data from the Khokana and Padhera Dovan stations in the Upper and Lower Bagmati River basin, respectively, for model calibration, validation, and sensitivity analysis. It employed the Sequential Uncertainty Fitting Algorithm (SUFI-2) of SWAT-CUP for calibration and identified several sensitive parameters that play a significant role in representing discharge, channel routing, and evapotranspiration losses in the river basin. During the calibration and validation periods, the model performance was evaluated using statistical indicators such as $R^2$ (coefficient of determination), NSE (Nash-Sutcliffe efficiency), PBIAS (percentage bias), and RSR (root mean square error to standard deviation ratio). The results indicated reasonable agreement between the simulated and observed discharge, demonstrating an acceptable model performance. The study also projected future changes in monthly discharge under two climate scenarios (SSP 2-4.5 and SSP 5-8.5) for the near future (2024-2050), future (2051-2075), and far future (2076-2100). The results indicated a decreasing trend in future discharge in certain months and an increasing trend in others, with higher precipitation intensity during the monsoon periods. The timing of the monsoon remained similar to the present in the near and far future under the SSP 2-4.5, while it shifted to starting soon in the near future, and till later months in the far future under SSP 5-8.5. The projected changes in discharge suggested a likelihood of amplified flood events in the Bagmati River basin in the future. Apart from flood events, both the outlets and neighboring areas have a high probability of facing water scarcity under the given future scenarios, especially during the dry seasons.

However, there is some uncertainty on projected future scenarios of discharges. There can be uncertainties in projecting future discharge scenarios due to various factors, including data accuracy, model parameterization, and climate model complexities. Despite reasonable agreement between observed and simulated discharge, data gaps and errors could introduce biases in the hydrological model's projections. Therefore, the future projections given by the model indicated potential changes in discharge patterns, emphasizing the importance of understanding the potential impacts of climate change on river hydrology. The implications could be on various sectors including water resources, agriculture, and hydropower. Decreasing discharge and amplified flood events during the monsoon could pose challenges in managing water resources, necessitating adjustments in water allocation. Water scarcity during dry seasons could lead to unmanaged water demands and affect agricultural practices. To address these uncertainties and potential challenges, adaptive measures such as optimizing water storage, implementing climate-resilient agriculture, and incorporating climate risk assessments for hydropower facilities are suggested. Therefore, the study emphasizes the need to understand climate change's potential impacts on river hydrology and the importance of adaptation strategies in the Bagmati River Basin.

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