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Impact of Climate Change on Future Flow Response in Marshyangdi River Basin, Nepal

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Abstract
Climate change significantly impacts rivers in mountainous catchments, implying that future water shortages and uncertainty of future changes are highly vulnerable to climate-related disasters such as flooding and landslides. The snow melt process is complicated, complex, and temperature dependent. The Hydrologic Engineering Center hydrologic modeling system (HEC-HMS) was used in this study to develop hydrological modeling along with the snowmelt method and investigate future discharge under Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5) in the Marshyangdi River Basin. Future precipitation and temperature data were used from the recent SSPs scenario for 2025 to 2100 under ten Coupled Model Inter-comparison Project, phase 6(CMIP6). At the basin outlet, calibration and validation were performed by importing precipitation, temperature, and a Digital Elevation Model (DEM) data. The projected precipitation, temperature, and discharge trends were obtained for three time periods: near future (NF), mid future (MF), and far future (FF). The maximum annual discharge are 337 m3/s (2043), 432.9 m3/s (2070), and 571.5 m3/s (2095) respectively under both scenarios. The maximum precipitation and discharge trend seen for FF are 53.88mm/year and 6.47 m3/s/year under SSP5-8.5 scenario, respectively, while the maximum temperature trend for NF is 0.061 ℃/year under SSP5-8.5. The maximum monthly discharge is 1535.5 m3/s for FF under SSP5-8.5 scenario. Overall the results show an increasing trend for NF, MF, and FF under SSP2-4.5 and SSP5-8.5 scenarios, but a decreasing trend in discharge for FF under SSP2-4.5 scenario as rainfall decrease for FF. Due to increased rainfall runoff and snowmelt runoff contribution due to temperature rise, discharge has the highest increasing trend under SSP5-8.5 scenario. Maximum future discharge has been observed in July under both scenarios for NF, MF and FF. These study's findings are expected to aware about the negative impacts of climate change in future flow and also develop different adaptation strategies to reduce the risk.

Keywords
CMIP6, SSP2-4.5, SSP5-8.5, HEC-HMS, Marshyangdi River Basin, Snowmelt

1. Introduction

Climate change is one of the world's most challenging issues today. Changes in ordinary climatic conditions and catastrophic events, are anticipated to have significant consequences for human and ecological systems[1].Climate change is projected to have an impact on water supplies by affecting hydrological variables like precipitation and temperature, which affect the hydrological cycle [2]. Climate change is the term used to describe any change in the climate through time, whether driven on by natural variability or human activity [3]. The 30 years from 1983 to 2012 were the hottest on record in the last 1400 years [4]. Since most of Nepal's major rivers are glacier-fed, continual changes in glacier reserves, snowfall, and natural disasters will have a significant impact on the nation's primary sources of water and hydroelectricity [5].

Hydrological models simulate the flows under various conditions or scenarios by representing the fundamentals of the hydrological cycle. This reproduces natural processes [6]. Hydrological models have a wide range of applications, including water resource planning and development, flood analysis, water quality and quantity, and the impact of climate change. HEC-HMS (Hydrologic Engineering

Center- Hydrologic Modeling System) is intended for usage in a wide range of geographic locations and applications in a variety of hydrological problems, such as runoff simulation and impact assessments [7]. The snowmelt approach in the Beas sub-basin near the Manali Bridge using the HECHMS model for analyzing snow bands known as stream flow synthesis and reservoir regulation (SSARR) [8]. For event and continuous simulation in high-altitude regions, the study used the HECHMS model (snow and glacier-fed)and the objective of the study is to combine several methods in the HECHMS model for daily stream flow projection in the basin under various climate scenarios and annual stream flows increased by 21.87 percent [9]. Modeling of snowmelt is used to forecast the volume of snow water equivalent and its effects on soil moisture, runoff, and stream flow [10]. Liquid water available at the soil surface (LWASS), which is used as an input to precipitation for predicting sub basin runoff, is the final output of the snowmelt method [10].

For climate projection, GCMs have several assumptions and uncertainties. Climate projection uncertainty is influenced by the factors such as greenhouse gas emissions, model structure, boundary conditions, downscaling approaches, and bias correction methods used [6]. Using the most recent CMIP6 GCMs, it was predicted that the annual mean temperature will rise by 2.1°C under SSP245 and 4.3°C under SSP585 by the end of the twenty-first century [11]. For a better simulation outcome, the appropriate choice of bias correction approach is critical. It has a significant impact on the simulation of stream flow. Data change method, Monthly mean correction, Linear Scaling, Gamma Quantile Mapping, General Quantile Mapping, and Power Transformation are some of the bias correction methods [12]. Water resource planning is difficult and challenging because of the variability and uncertainty of future changes caused by climate change [13]. Marshyangdi basin where a snow-fed region is present, the snowmelt method should be used and the contribution of snowmelt must also be considered when projecting river flow. In a previous study, the effect of climate change on stream flow in the Marshyangdi river basin, an average discharge of 204.03 m3 (1988–2009) showed a decrease in rainy days while an increase in the intensity of excessive rainfall, and projected precipitation based on downscaling suggested a rise in precipitation for the 2050s [14]. The model's output indicated that snowmelt contributed 20% of the total stream flow in the Marshyangdi River, and that contribution increased by 29% and 38% under RCP4.5 and RCP8.5 scenarios, respectively [15].

The overall objective of this study is to analyze the impact of climate change on future flow under different climate change scenarios of the Marshyangdi River Basin. The specific objective of the study are: i) to develop hydrological modeling in HEC-HMS taking into account snowmelt runoff contribution in the Marshyangdi River Basin; ii) application of HEC-HMS model for continuous flow simulation under Shared Socioeconomic pathways (SSPs) scenarios; and iii) to obtain future discharge trend for near future, mid future and far future period.

2. Study area

The research area includes the Marshyangdi River basin, which passes across Nepal's western region. Manang, Lamjung, Gorkha, and Tanahau are the four districts that make up the river basin, which flows through the Annapurna mountain range's northern slope. It can be found between the latitudes of 27°56'13"N and 28°54'03"N, and the longitudes of 83°47'23"E and 84°41'51"E. At the intersection of two mountain rivers, the Khangsar Khola and the Jharsang Khola, the Marshyangdi begins. The Marshyangdi River has four significant tributaries: Nar Khola, Dudh Khola, Dordi Khola, and Chepe Khola. The study area covers an area of 4051.65 square kilometers. The elevation of the study area

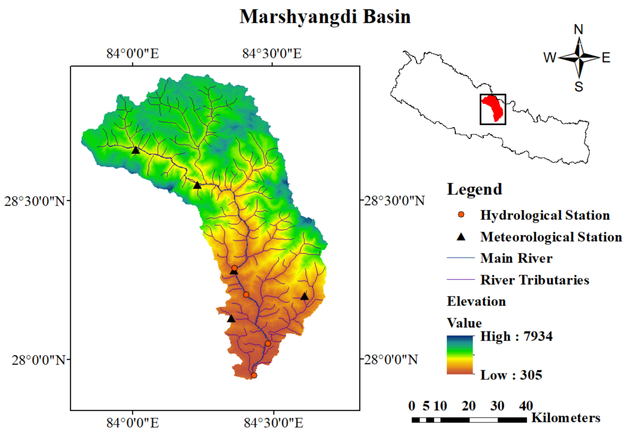

Figure 1: Location map of the study area

varies from 305m.a.s.l. to 7934m.a.s.l. Most of the region lies above 3000m.a.s.l. The mean slope of the basin is 29°. The Marshyangdi River runs east through Manang district and south through Lamjung district. This basin's Marsyangdi River is a tributary of the Narayani River System, which finally joins with the Ganga River [16].

3. Data collection and methodology

3.1 Data collection

3.1.1 Hydrology and meteorology

Hydro-Meteorological data were collected from the Department of Hydrology and Meteorology (DHM), Nepal. Overall, five meteorological stations were used in this study, and daily observed precipitation data were collected for station no. Khudi bazar (802), Kunchha (807), Chame (816), Manang bhot (820), and Gharedungha (820) where daily observed temperature data was only for station khudibazar (802) and Chame (816). The meteorological data are precipitation, maximum temperature, and minimum temperature data. The daily observed Meteorological data from DHM range from the year 1961 to 2017. The study area included a total of four hydrological stations: Khudi khola at Khudi Bazar (439.29), Marshyangdi River at Bimal Nagar (439.7), Chepe Khola at Garam Besi (440), and Marshyangdi River Bhakundebesi (439.35). Out of four stations, Bimalnagar (439.7) was chosen for the study, and daily observed data were gathered for this station from 1988 to 2010. This point was considered the basin's outlet point when calibrating and validating the model.

3.1.2 Topography

The topography of this research area was determined using a digital elevation model with a resolution of 12.5 meters available in Geo TIP file format. This can be downloaded from the Earth Observing System Data and Information System website (https://www.earthdata.nasa.gov/) and used in the ARC Map Software to create a hydrological model. There are 30m resolution DEM available, but the study used high-resolution DEM, which provides better results with higher accuracy. This DEM file was imported into the HEC-HMS model and GIS processing was performed to obtain Sub-basin characteristics such as flow path length, the basin slope, basin relief, and drainage density. The elevation ranges from 305m to 7934 m and most of the area is above 3000m and elevation wise DEM of the study is shown in figure 2.

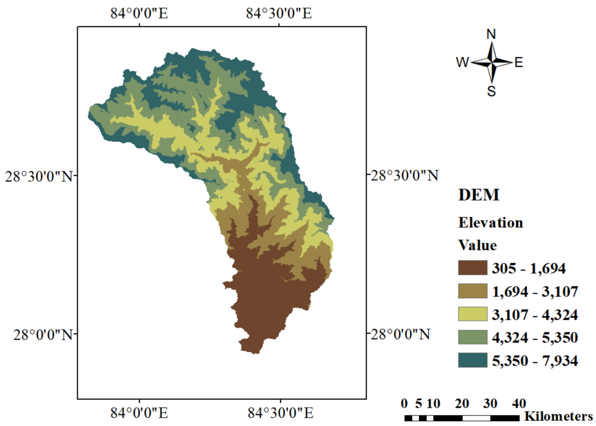

Figure 2: DEM of the study area

3.1.3 Future climate data

For the analysis of climate change's impact on hydrology, future data on precipitation and temperature is required. The selection of a climate model is an essential aspect of any research project. The research areas projected future climate data was collected from the Coupled Model Inter-comparison Project (CMIP6) portal under different general circulation models (GCMs). Based on the Shared Socio-economic Pathway (SSP) scenarios, CMIP6 data was used are SSP2-4.5 and SSP5-8.5 and downloaded from World Climate Research Programme CMIP6 website https://esgf-node.llnl.gov/projects/cmip6/. With the ESM (Earth System Model) model, an improved version of ACCESS (Australian Community Climate and Earth System Simulator) 1.0 from CMIP6 was used in this study. The equilibrium climate sensitivity of ACCESS-ESM1.5 is 3.87°C, according to an analysis of the climate's response to CO2 forcing [17]. The SSP2 4.5 and SSP5 8.5 data for two coordinates located in the study area were downloaded at latitudes of 28.125, 28.375, and longitudes of 84.125, and 84.375, respectively. The final data used for further analysis was the average of these two coordinate data.

3.2 Methedological framework of the study

The first stage of the study involves creating a hydrological model utilizing historical DHM data for a number of sub-basins, including contributions from snowmelt. Following this, future river flow was predicted using data on future precipitation and temperature from various GCMs.

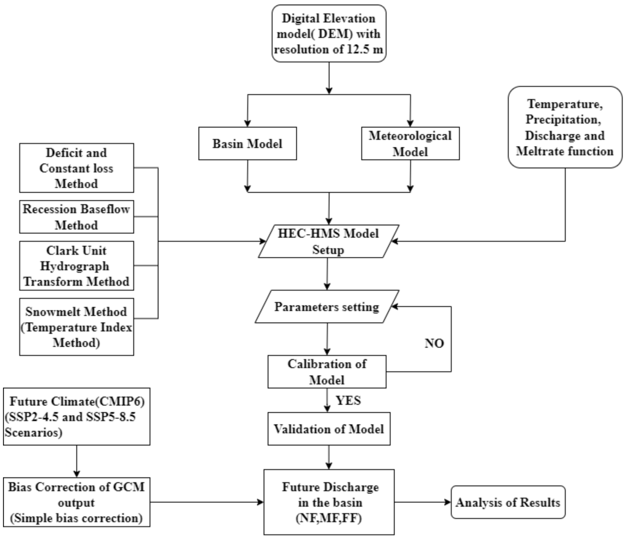

Figure 3: General framework of the study

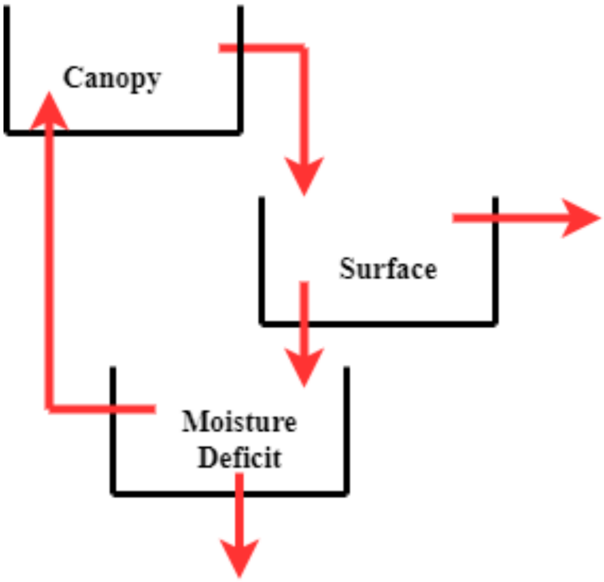

Figure 4: Schematic diagram of deficit and constant loss

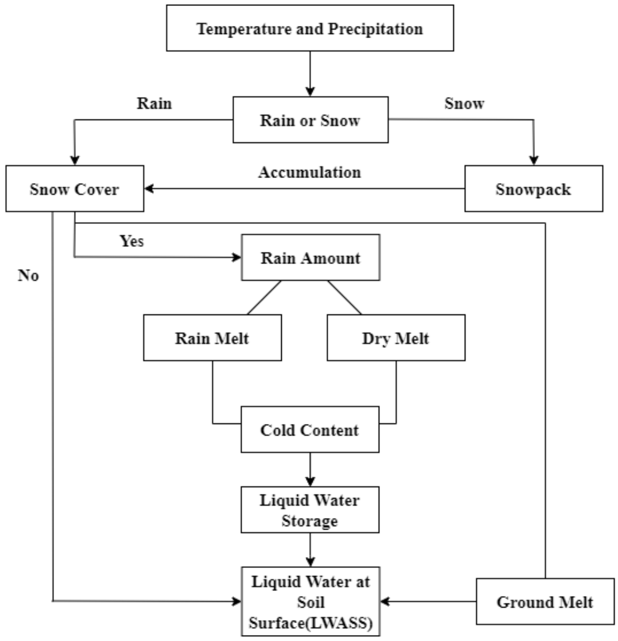

Figure 5: Flowchart of snowmelt algorithm in HEC-HMS

3.3 Hydrological model setup

The Hydrologic Engineering Center hydrologic modeling system (HEC-HMS) is intended for continuous and event-based hydrologic modeling. It provides the user with a number of modeling options for various components of the hydrologic cycle. The latest HEC-HMS version 4.10 was used for the hydrological model setup. This river basin's catchments are primarily snow-fed and contribute to runoff.The snow model was chosen using the temperature index approach to model sub-catchments. The methodology under the loss method and snow model that is used to address the study's aims is shown in figure 4 and figure 5.

3.3.1 Basin model

A basin model is one of the most important parts of a project. The basin model was created in the model using the Basin model manager. The terrain data was used to prepare the study area's basin. The digital elevation model with a resolution of 12.5 m was imported into the basin model using the terrain data manager. By completing the GIS process (preprocess sinks, preprocess drainage, identify streams, and delineate elements), the number of sub-basins, reach, junctions, and sink (outlet) was developed as shown in figure 6. There are eight sub-basin, four junctions, and five reach elements present in the basin.

3.3.2 Control specification

Control specifications are important to set for the calibration and validation of a model. They should be chosen so that the chosen period has continuous data for several years because most hydro-meteorological stations have missing data. The main aim is to control the simulation's start and stop times and the time intervals.

3.3.3 Time series data

The precipitation, temperature, and discharge time series data were imported into the model using the time series data manager and given precipitation

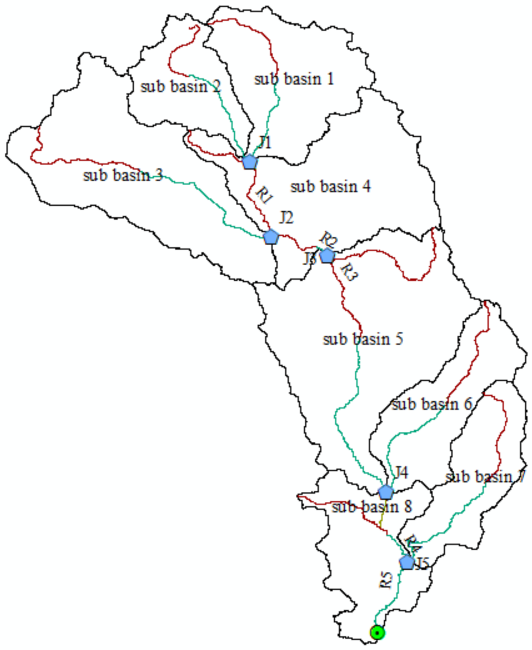

Figure 6: Basin model in HEC-HMS model

gages, temperature gages, and discharge gages, respectively. The hydrological model needs time series data on precipitation to determine the average rainfall in a basin. There were gaps in some of the time series data, which were filled and then used in the model.

3.3.4 Meteorological model

One of the key elements of the model setup is meteorological models. This component provided each sub basin's meteorological boundary condition. Meteorological models defined specified hyetographs for precipitation and specified thermographs for temperature in the model setup. The model contains eight sub-basins, and each sub-basin specified a rainfall station that is included in the sub-basin in order to estimate the sub-basin rainfall for precipitation and the same for temperature.

3.4 Methods used in the model

3.4.1 Deficit and constant loss method

Several processes, including infiltration, surface runoff, and subsurface processes, occur in each sub-basin. The loss method was used to calculate the rate of infiltration. This method used a single soil layer for continuous flow simulation. This method is combined with the simple canopy and simple surface methods. The input parameters for the deficit and constant loss method are initial deficit, maximum deficit, constant rate, and impervious.

3.4.2 Recession base flow method

After precipitation in a sub-basin contributes to infiltration, surface runoff, and subsurface processes, the base flow method was used to determine the actual subsurface. The model provides a total of six different base flow method types. The base flow of the river was calculated using the recession base flow method. Initial discharge, Recession constant, Threshold type, and ratio are the input parameters for this method.

3.4.3 Clark unit hydrograph transform method

The Clark unit hydrograph model was applied as a transform method for calculating the watersheds direct runoff volumes. It is the process by which excess precipitation becomes runoff. The storage of water in the soil, the surface, and through channels is important for the transformation of excess precipitation into the runoff. Time of concentration and storage coefficient are the parameters used in the transformation process.

3.4.4 Flow routing

"Reach" refers to a river segment with one or more inflows and only one outflow. There are nine different ways to route the river's flow [18]. The lag method has been selected for routing flow in the MRB, and the input parameter used for this method is lag time.

3.4.5 Snow melt method

The hydrological process heavily depends on snowmelt. Snowmelt contributes to the flow both in the winter and the summer. Wet melt (in the presence of rain) and dry melt (in the absence of rain) are the two conditions in which melting can occur. The amount of water in the snowpack was determined by SWE. SWE measures the depth of water that is melting from the snowpack. The snow melt model includes the temperature index method and the gridded temperature index method. There are two methods for calculating snowmelt from the snowpack. The energy balance method and the temperature index or degree-day method currently, only the degree day approach is available in HEC-HMS [19]. This study used the temperature index method for the snow melt model. The degree-day approach to modeling snowpack was used in this method. The temperature index is the difference between air and base temperatures used to calculate snow melt. The basic equation is given by:

$$M_S = C_m(T_a - T_b) \quad \text{if } T_a > T_b$$
$$= 0 \quad \text{if } T_a \le T_b \tag{1}$$

Where, M_S = snowmelt contribution in mm/ day; T_a = air temperature in °C, air temperature is the mean of daily maximum and minimum temperature; T_b = base temperature in °C and it is taken as 0°C; C_m = melt rate coefficient and it is multiplied by ATI -melt rate coefficient. Melt rates are classified as wet and dry melt rates according to rainfall and rain rate limits. The melt rate coefficient was determined by a calibration process in the model and its value ranges from 0 to 1.

3.5 Bias correction

The biases can be attributed to systematic model flaws brought on by inadequate conceptualization, discretization, and spatial averaging within the grids[20].Various methods are available for bias correction of daily time series data precipitation and temperature. The following equation were used for bias correction of Precipitation and temperature data in this study [20]:

$$T_{\text{Corrected}} = T_{SCEN} - (\bar{T}_{\text{CONT}} - \bar{T}_{obs})$$
$$P_{\text{Corrected}} = P_{SCEN} \times \left(\frac{\bar{P}_{\text{obs}}}{\bar{P}_{\text{CONT}}}\right) \tag{2}$$

Where, $T_{\text{Corrected}}$ and $P_{\text{Corrected}}$ are bias-corrected daily temperature and precipitation data respectively; $\bar{T}_{obs}$ and $\bar{P}_{obs}$ are monthly mean of observed temperature and precipitation respectively; T_{SCEN} and P_{SCEN} are daily temperature and precipitation data from GCM and RCM scenarios; $\bar{T}_{CONT}$ and $\bar{P}_{\text{CONT}}$ are monthly mean temperature and precipitation from historical scenarios respectively. According to the study, mean based techniques from the above equation are easy to understand, straightforward to apply, and equally effective for analysis [21].

3.6 Climate change impact assessment

The influence of climate change on MRB was assessed using flow discharge simulations from the HEC-HMS model.Future climate data was collected from 2025 to 2100, and they were classified as near, mid, and far future in the basin for the future periods 2025-2050, 2050-2075, and 2075-2100 respectively. For flow projections from 2025 to 2100, bias-corrected data from two shared socioeconomic pathways, SSP2-4.5 and SSP5-8.5, were used to project future flow.

3.7 Model Calibration and validation

The model was calibrated for the first five years, 2000 to 2004, and then validated for the next five years, 2005 to 2009. Calibration and validation were carried out at the model's sink or the basin outlet (Bimalanagar station). As performance evaluation indices, hydrological model quality was assessed using the Nash-Sutcliffe efficiency coefficient (NSE), percentage bias (PBIAS), and determination coefficient (R^2).

4. Results and discussion

4.1 Calibration

The calibration and validation of the model were done at the outlet point of the basin (Sink). The model's simulated hydrograph and observed flow hydrograph for volume calibration is shown in figure 7. Calibration was done for volume and peak discharge separately. The scatter plot diagram of the volume calibration is given in figure 9. The best fit line shows good harmony between observed and simulated discharge except for peak discharge values that are more deviated. The volume from the observed flow is 9055.91 mm and 8776.85 mm from the simulated flow.

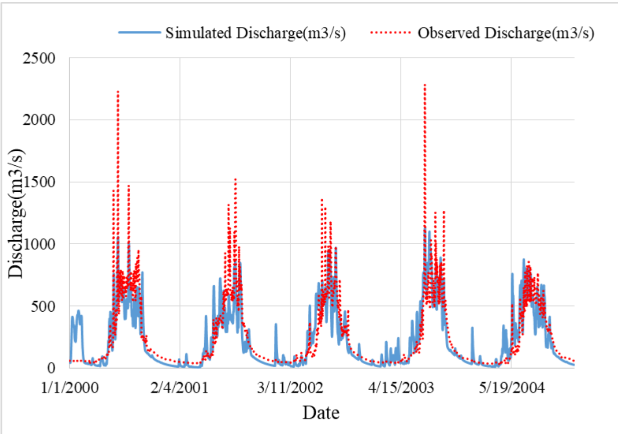

Figure 7: Volume calibration results from 2000 to 2004

For peak discharge calibration, the model was simulated to match the peak discharge of the observed and simulated flow in the basin because the peak value is usually underestimated and is one of the limitations of hydrological modeling. The observed and simulated peak discharges are 2270 m3/s and 2270.7 m3/s, respectively for peak discharge calibration. Figure 8 represents the observed and simulated hydrograph for peak discharge calibration.

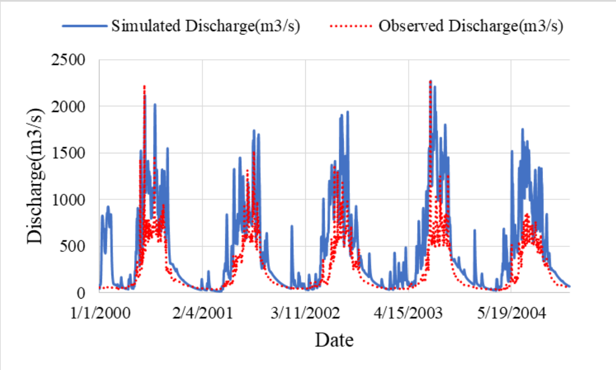

Figure 8: Peak discharge calibration result from 2000 to 2004

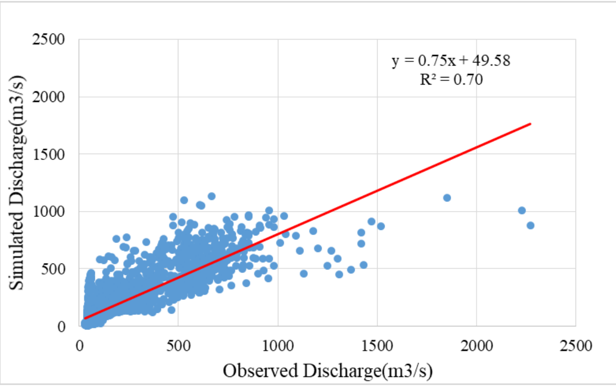

Figure 9: Comparison model of observed and simulated discharge for volume calibration

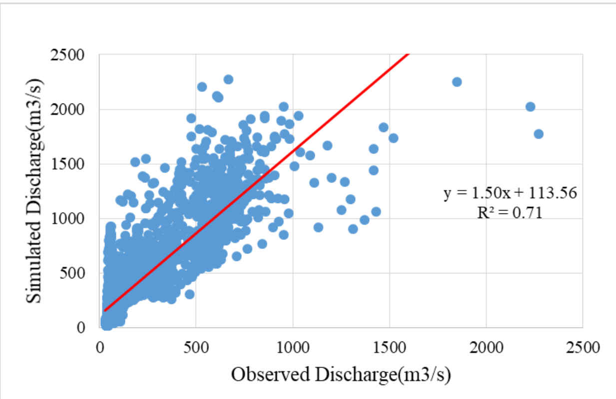

Figure 10: Comparison model of observed and simulated discharge for peak discharge calibration

The scattered plot diagram with the line of best fit is shown in figure 10 for peak discharge calibration and shows satisfactory agreement between the observed and simulated data. The calibrated parameter values for eight sub-basins are shown in table 1 and table 2 and calibration was performed through manual calibration by the trial method.

Table 1: Calibrated parameters for each sub-basin

Parameters	unit	Value
Initial Storage Canopy	mm	1
Maximum Storage Canopy	mm	2
Initial Surface Storage	mm	0.01
Maximum Surface Storage	mm	6
Constant Rate	mm/hr	0.15
Clark Storage Coefficient	hr	58
Recession Constant		0.98

Table 2: Temperature index calibrated parameters

Parameters	Unit	Value
Index	mm	25
PX Temperature	°C	2
Base Temperature	°C	0
ATI Coefficient		0.95
Wet Melt Method		Constant Value
Wet Melt rate	mm/°C-day	7
Rain Rate Limit	mm/day	20
Dry Melt Method		Fixed Value
Dry Melt rate	mm/°C-day	8
Cold Limit	mm/day	1.1
Cold rate Coefficient		0.2
Water Capacity	%	8
Ground melt Method	mm/day	2

4.2 Validation

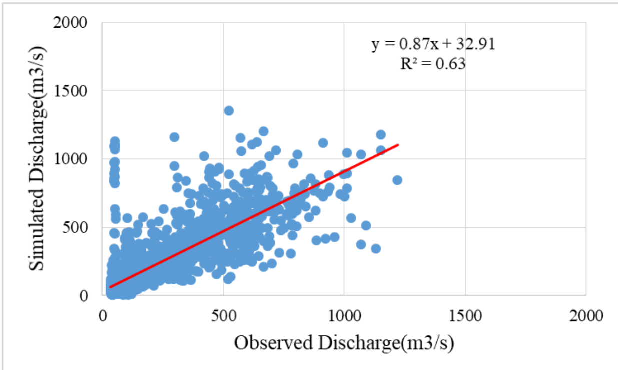

Figure 11: Comparison model of observed and simulated discharge for volume validation

After the calibration process was completed, the calibration parameter was fixed and the model was validated from 2005 to 2009. The hydrograph comparison of the observed and simulated flow for model validation is shown in figure 13. The model performs satisfactory agreement between observed and simulated discharge for the scattered plot under volume validation results as seen in figure 11. According to the model, the volume and peak

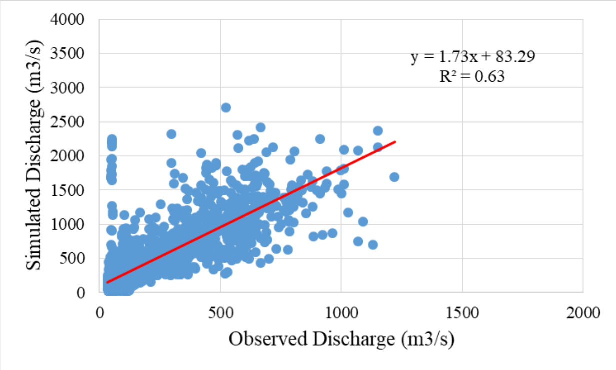

Figure 12: Comparison model of observed and simulated discharge for peak discharge validation

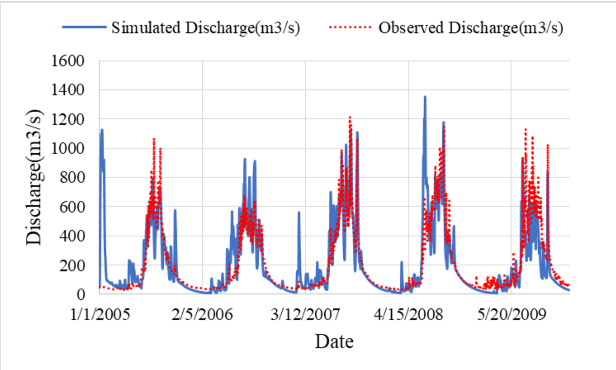

Figure 13: Volume validation results from 2005 to 2009

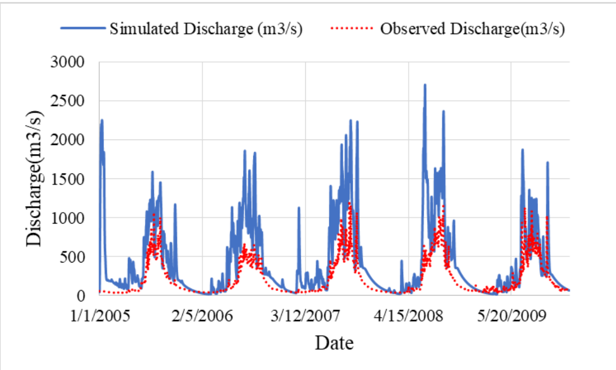

Figure 14: Peak discharge validation results from 2005 to 2009

discharge are 8286.08mm and 1353.7 m3/s, while the volume and peak discharge determined by the observed data are 7995.73mm and 1220 m3/s, respectively for volume calibration. Figure 12 and figure 14 show the peak discharge validation and the scatter plot between simulated and observed discharge. The data are more scattered between observed and simulated discharge. The volume calibration model was used for further analysis.

4.3 Hydrological model performance

Table 3 and table 4 show the ratings for R2, NSE, RMSE, and P Bias, which are used to assess how well both calibrated and validated models perform. The ratings given to the model are very good, good, satisfactory, and poor. RMSE, NSE, P Bias, and R2 for the calibrated model have values of 0.5, 0.704, -3.09, and 0.71 respectively. For validation, RMSE, NSE, P bias, and R2 have values of 0.7, 0.549, 3.62, and 0.64 respectively.

Table 3: Performance criteria values for calibrated model

Criteria	RMSE	NSE	P Bias	R^2
value	0.5	0.704	-3.09	0.71

Table 4: Performance criteria values for validated model

Criteria	RMSE	NSE	P Bias	R^2
value	0.7	0.549	3.62	0.64

For calibration, the rating for PBIAS shows excellent results that fall in the range of ± 5%, and the value of RSR (RMSE Std. Dev) is between 0 to less than equal to 0.5, which shows good performance of the model. The NSE value of the calibration model is 0.704, which lies between 0.7 to less than equal to 0.8, which performs a good model rating. The value of the coefficient of determination R2 is 0.71, falling between 0.6 to less than equal to 0.75, which shows a satisfactory rating. The overall performance of the calibrated model meets the evaluation criteria.

For validation, the PBIAS value is +3.62% that fall in the range of ± 5% , showing that the model is very good, and the value of RSR (RMSE Std. Dev) is 0.7 which lies between 0.6 to less than equal to 0.7 shows the satisfactory result. The NSE value is 0.549 which lies between 0.5 to less than equal to 0.7, indicating that the model is only satisfactory. When compared to the calibration result, the NSE value has decreased. The coefficient of determination R2 value is 0.64, which is also lower than calibration and delivers a satisfactory result. Based on the model's overall performance after validation, the model can be used to forecast future flow in the basin.

4.4 Future discharge trend

The future discharge was calculated using a calibrated and validated model in HEC-HMS by importing future temperature and precipitation data with bias correction for two SSP scenarios. The future discharge was split into three time periods: the near future (2025-2050), the mid-future (2050-2075), and the far-future (2075-2100).

Table 5: Summary of precipitation, temperature, and discharge trend for SSP2-4.5 and SSP5-8.5 (NF-2025 to 2050, MF- 2050 to 2075, and FF- 2075 to 2100)

Scenario	Parameters	NF	MF	FF
SSP2-4.5	Precipitation (mm/year)	12.16	10.37	-26.74
	Temperature(°C/year)	0.02	0.028	0.044
	Discharge (m3/s/year)	1.543	1.562	-4.54
SSP5-8.5	Precipitation (mm/year)	15.18	29.28	53.88
	Temperature(°C/year)	0.061	0.05	0.053
	Discharge (m3/s/year)	1.218	2.8	6.47

Table 5 shows the projected annual discharge, precipitation, and temperature trends for both scenarios throughout three different time frames. Table 5 shows the discharge from 2025 to 2050 with a positive trend for both scenarios. According to the SSP2-4.5 scenario, the annual discharge for MRB will increase by 1.543 m3/s from 2025 to 2050, compared to 1.218 m3/s for NF under the SSP5-8.5 scenario. The maximum annual discharge has been seen in 2043 for the near future is 337 m3/s. According to study, the Modi Khola, which is close to the study region, is gradually increasing its discharge [22]. Another study also shows an increasing discharge trend in the Annapurna region [20]. Both scenarios have a rising trend in annual precipitation and temperature in the near future period. Four downscaling methods (SDSM, PRECIS, RegCM, and WRF) for the projected precipitation was performed from 2030 to 2050 using the A1B scenario and the findings indicate an increasing trend throughout all methods are 5.98 mm/year, 19.68 mm/year, 8.26 mm/year, and 87.92 mm/year, respectively [14]. According to our research, the SSP2-4.5 scenario and the SSP5-8.5 scenario both show an increasing trend from 2025 to 2050 of 12.16 mm/year and 15.18 mm/year, respectively (table 5). Additionally, SSP2-4.5 and SSP5-8.5 also exhibit an increasing temperature trend of 0.02 °C/year and 0.061 °C/year, respectively for NF (table 5). The flow in the basin is rising due to the rising temperatures and precipitation.

Table 5 shows the upward trend (precipitation, temperature, and discharge) under both scenarios from 2050 to 2075 (Mid-future). The discharge rises by 1.562 m3/s annually in SSP2-4.5 and by 2.80 m3/s in SSP5-8.5 scenario for MF. The increasing trend is higher for the SSP5-8.5 than for the SSP2-4.5 scenario. The year 2070 for the middle of the future has the highest annual discharge of 432.9m3/s. The rising precipitation of 10.37 mm/year and 29.28 mm/year, as well as the rising temperatures of 0.028 °C/year and 0.05 °C/year under SSP2-4.5 and SSP5-8.5, respectively for MF (table 5), are the reasons of the basin's rising discharge trend.

From table 5, the discharge trend in SSP5-8.5 is increasing and decreasing in SSP2-4.5 for FF. The SSP5-8.5 scenario increases by 6.47 m3/s per year, whereas the SSP2-4.5 scenario decreases by 4.546 m3/s per year for FF. This decrease in basin flow is due to a decrease in rainfall of -26.74 mm/year for far future but the temperature is in the increasing trend of 0.044 °C/year under SSP2-4.5 scenario. As shown in figure 17 and figure 20, the flow in the basin is gradually decreases from 2075 to 2100 under SSP2-4.5 and, the minimum annual discharge is 152.62 m3/s in 2087. According to SSP5-8.5, the discharge is expected to increase as precipitation of 53.88 mm/year and temperature of 0.053 °C/year for FF. The maximum annual discharge of 571.5 m3/s has been observed in the 2095 for the far future period under SSP5-8.5 scenario. The maximum discharge and maximum discharge trend is seen for FF under SSP5-8.5 scenario. The increasing flow in the basin is also a factor, as snowmelt contributes to runoff. The temperature trend shows the increase in both scenarios that help to contribute snowmelt runoff. The maximum discharge predicted for the end of the century may include more snowmelt melt contribution as well as rainfall contribution.

For NF, MF, and FF under both scenarios, the projected annual discharge and precipitation are shown in the figures 15, 16, and 17. According to the figure 17, the annual discharge and precipitation for FF under SSP2-4.5 continue to decrease. Figures 18, 19, and 20 represent the projected annual discharge and temperature for NF, MF, and FF under both scenarios. In the figure, the projected discharge is compared to precipitation and temperature. According to the projections, annual discharge, precipitation, and temperature for FF will all rise rapidly under the SSP5-8.5 scenario from figure 17 and figure 20. Under RCPs, the study in the Modi River Basin show that future discharge will increase during later time windows, i.e, far future (2075-2099) >>mid future (2050-2074) >>near future (2025-2049) and this study also shows discharge trend are increasing more towards FF [23].

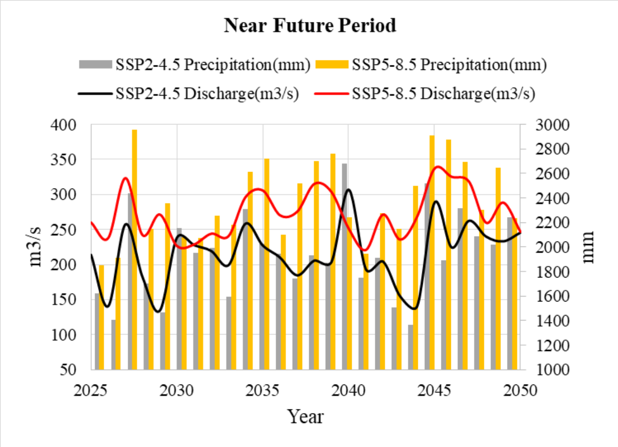

Figure 15: Comparison of projected annual discharge and precipitation from 2025 to 2050

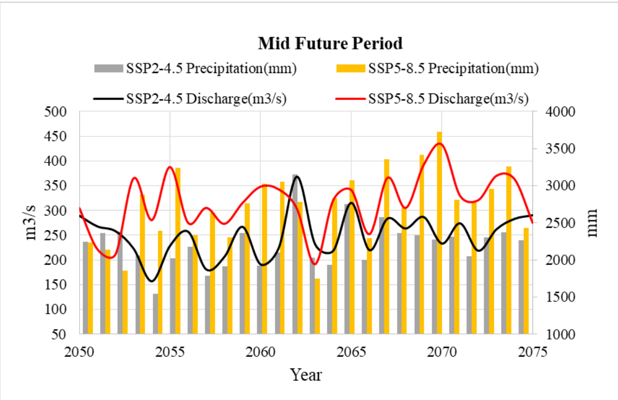

Figure 16: Comparison of projected annual discharge and precipitation from 2050 to 2075

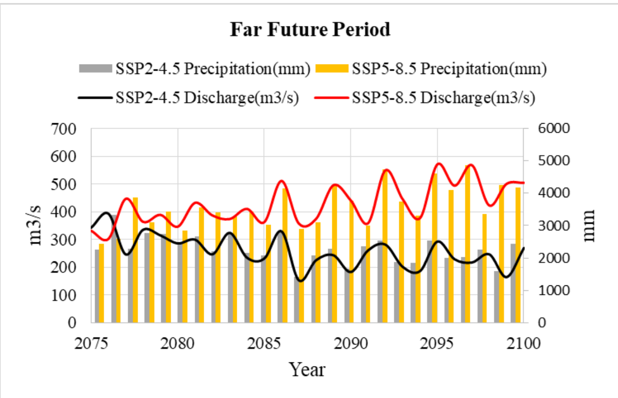

Figure 17: Comparison of projected annual discharge and precipitation from 2075 to 2100

The maximum monthly observed discharge was seen in August (660.7 m3/s) and maximum discharge for

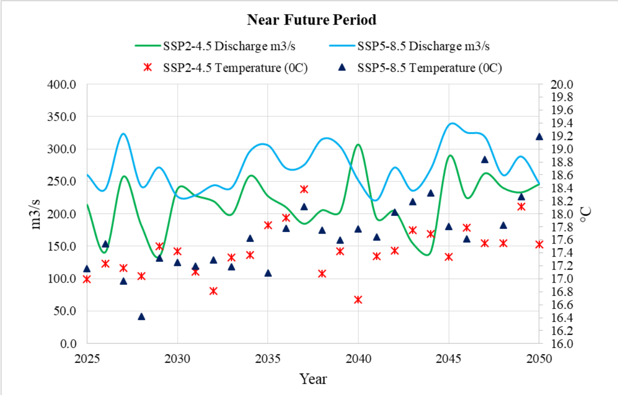

Figure 18: Comparison of projected annual discharge and temperature from 2025 to 2050

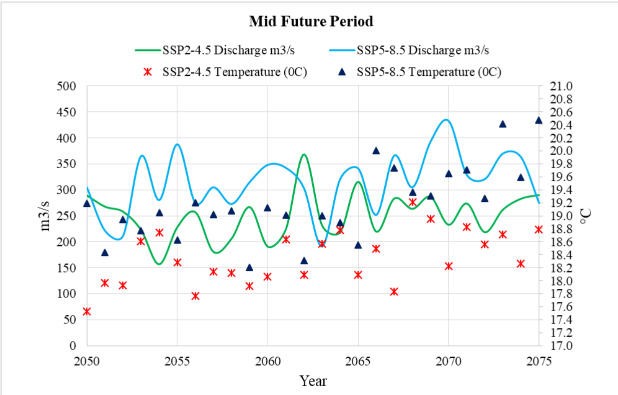

Figure 19: Comparison of projected annual discharge and temperature from 2050 to 2075

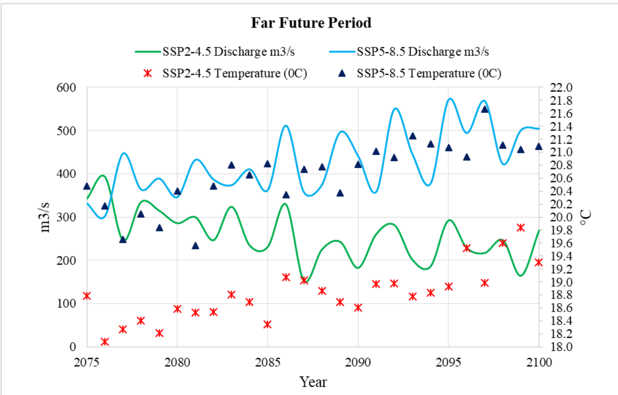

Figure 20: Comparison of projected annual discharge and temperature from 2075 to 2100

three different future periods (NF, MF, and FF) has been seen in July under both SSP2-4.5 and SSP5-8.5 scenarios from figure 21. The maximum monthly discharge for NF, MF, and FF are 846.8 m3/s, 943.1 m3/s, and 909 m3/s under SSP2-4.5 scenario respectively. Similarly, the maximum monthly discharge for NF, MF, and FF are 1059.6m3/s, 1224.8 m3/s, and 1535.5 m3/s under SSP5-8.5 scenario respectively.

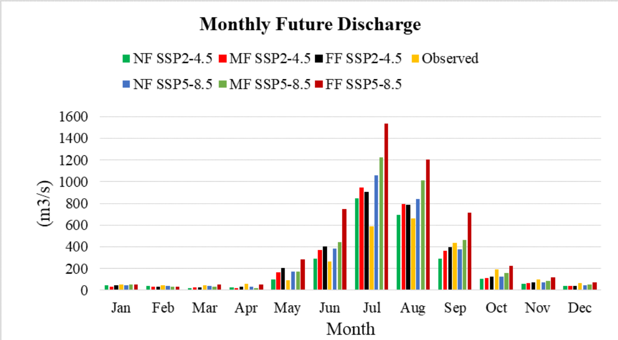

Figure 21: Monthly future discharge for three different periods (NF, MF, and FF) under SSP2-4.5 and SSP5-8.5

5. Conclusion

The HEC-HMS model was built with snowmelt as the temperature index method and future corrected precipitation and temperature data to predict future flow in the basin. The model shows good agreement between observed and predicted flow after being calibrated and validated at the basin outlet. For projecting basin discharge, three time periods were used: near future (NF), mid future (MF), and far future (FF). Precipitation, temperature and discharge show an increasing trend for all time periods under SSP2-4.5 and 8.5, but a decreasing discharge trend for FF under SSP2-4.5 scenario.

Under SSP5-8.5, the discharge has the highest increasing trend due to increased rainfall runoff and snowmelt runoff contribution due to temperature rise. The melting of snow on MRB is also a major factor in the increase in river flow for SSP5-8.5. For both scenarios, the maximum discharge was seen in July for monthly projected discharge and monthly maximum discharge has been found 1535.5 m3/s for FF under high scenario. The maximum annual discharge for NF, MF, and FF are 337 m3/s (2043), 432.9 m3/s (2070), and 571.5 m3/s (2095), respectively under both scenarios. The results from this study can be provided to local governments and communities to help them cope with the adverse effects of climate change in the study area and also to the planning of water resources, irrigation, hydropower, and the design of various structures related to river flow.

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