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Climate Change Investigation of Swat River Using HEC-HMS Hydrological Model

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Abstract: Pakistan is included in the most water stressed countries in the world and its water resources are vulnerably affected by the climate change. Monitoring regional watershed can help to secure resources for upcoming future. Our research is based on understanding of hydro- climatic regime of Swat River basin up to Khawaza Khela using physical based HEC-HMS model. The Model was calibrated and validated on daily scale and evaluated using statistical performance indicator to able to provide desired performance range. The calibration and validation of Nash-Sutcliff Coefficient were recorded 0.84 and 0.81, the Root Mean Square Error (RMSE) were recorded as 5.5 and 2.8, and the coefficient of determination (R^2) results in 0.86 and 0.84 respectively. Furthermore, for climate change analysis two scenario: Representative Concentration Pathway (RCP) 4.5 and RCP8.5 of MIROC5 hydrological model were investigated and both the scenarios were incorporated into the selected model for future use, which showed increase in precipitation for both RCPs. At the end of century total annual rise of +195mm (14.8%) was observed for RCP8.5 and 119mm (9%) was observed for RCP4.5. On seasonal basis winter precipitation seems to grow over the century and other seasons remain slightly random. Analysis of river flow seems to predict higher magnitudes of flow. Likewise, at the end of century, RCP4.5 suggest 38.9% increase in flows and RCP8.5 showed 40.9% increase in flow. Seasonal analysis reveals that highest positive deviations were recorded during the season of monsoon and autumns for stream flow.
Keywords: RCP analysis, Hydrological model, MIROC5 model, Climate change investigation

I. INTRODUCTION

According to the various RCP (Representative Concentration Pathway) scenarios [1], there are numerous probable projected variations in the climate system. According to several studies conducted around the world, global surface temperatures are expected to increase in the twenty-first century under all assessed emission scenarios by increasing the number of deaths [2] [3]. Climate changes such as local precipitation and temperature, according to the Intergovernmental Panel on Climate Change (IPCC), has been blame for a rise in water-related risks (e.g., floods and droughts). These extreme precipitation events will become more intense with large amount of uncertainties because large amount of studies on the precipitation are modal based [4]. This type of threat is particularly dangerous in developing nations, such as Pakistan, where agriculture employs 40% of the population [5].

Pakistan has five important rivers that flow through its territory (the Indus, Jhelum, Chenab, Ravi, and Sutlej), yet all of these rivers are trans-boundary and originate/flow through India's neighbouring state. In 1960, Pakistan and India signed the Indus Waters Treaty (IWT), under which India received the water of three eastern rivers (Ravi, Sutlej, and Beas) and Pakistan received the water of three western rivers (Indus, Jhelum, and Chenab). Pakistan built two mega dams, eight link canals, and five barrages after signing the IWT–1960 to address water shortages caused by the unavailability of water from the Eastern Rivers (WAPDA, 2013) [6]. Glaciers and snowmelt account for about 40% of the average annual Indus River flow. Throughout the months of July and August, over 70% of the annual Indus River flow is created. Due to glacier and snowmelt, peak stream flow occurred during these months [7][8]. Climate change is projected to produce changes in seasonal stream flow patterns (possibly resulting in catastrophic flooding) in the Indus basin, posing new water management concerns.

The Swat River is critical to Pakistan's future economic development [9]. On the Swat River, there are three hydroelectric stations with a combined operational capacity of 123 MW. Another hydroelectric power producing station (Munda Dam) is being built on the Swat River at the time of writing, with an estimated capacity of 740 MW. This dam will irrigate 15,100 acres of land as well as generate energy [10]. They would also safeguard the Charsadda and Nowshera areas from floods, which were severely impacted by flooding in 2010. The Swat River basin is located between 34°00′ north and 35°56′ north latitude and 70°59′ east and 72°47′ east longitude [11].

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To address the limitations of the current literature, in this article we have ascertained various significant factors that play critical role in the investigation of climate change of Swat River. We expect that our results and conclusion will provide basis to all researcher to better plan and execute their analysis. To carry out our research, we have utilized the well-known HEC (Hydrological Engineering Centre) and HMS (Hydrological Modelling System) Hydrological model. Based on this model the calibration and validation of Nash-Sutcliff Coefficient were recorded 0.84 and 0.81, the Root Mean Square Error (RMSE) were recorded as 5.5 and 2.8, and the coefficient of determination (R2) results in 0.86 and 0.84 respectively.

Remainder of this paper is structured as follows: Section 2 enlightens the main objective of this research study. Section 3 describes the methodology used. In section 4, we discussed and analyse our results. Finally, Section 5 presents the conclusion and open questions for future research.

II. RESEARCH OBJECTIVES

In order to carry out our research study, we have designed it into the following formulated objectives:

1) A study of the Swat Basin's projected climate change by applying HEC-HMS model
2) Assessment of the Swat River's inter-annual and seasonal flows as a result of climate change.

III.METHODOLOGY

A. Study Area

The study is carried upon river swat catchment area which is in the northern region of Khyber-Pakhtunkhwa Province, Pakistan. The river commences in the Kalam Valley of Swat Kohistan with the confluence of two main tributaries Ushu and Utrar (or Gabral) and runs downstream in a narrow gorge up to Baghdheri as shown in figure 1 below. The Swat River basin catchment lies between a latitude of 34°00′ north to 35°56′ north and longitude 70°59′ east to 72°47′ east [12].

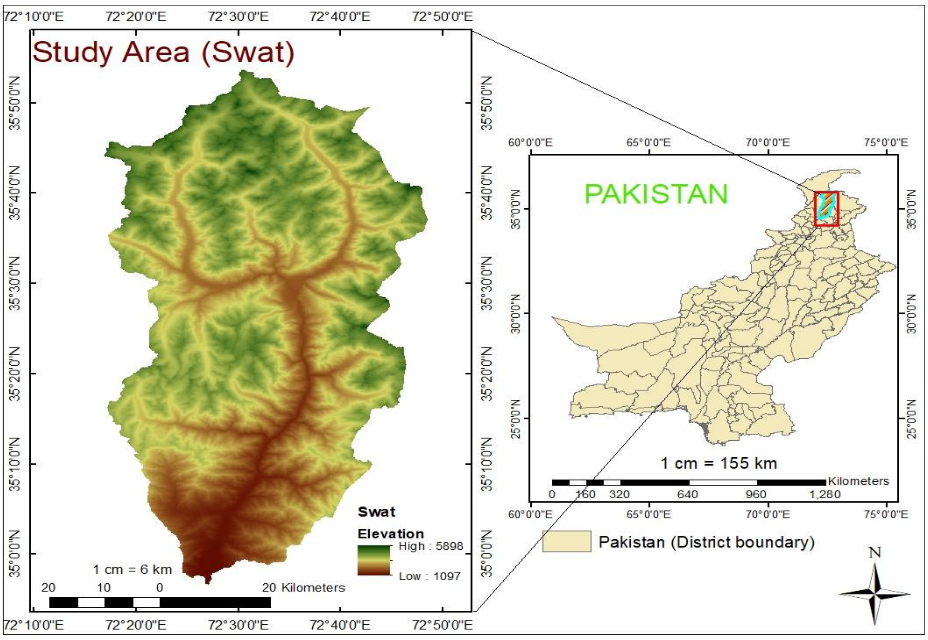

Figure 1. Location of Swat River basin

B. Methodological Framework Of The Study

In order to obtain the desired results, we have divided our methodological framework into various steps as depicted in figure 2 below. It is necessary to extract the SRTM (Shuttle Radar Topography Mission) of the region comprising the territory of the selected research study to delineate the watershed of the Swat River basin [13]. The extracted data is then processed in Arc GIS (Arc Hydro tool) to get the Swat basin's watershed DEM, which is used to determine the basin's elevation. Furthermore, Landsat 8 satellite imagery is downloaded and processed in Arc GIS to determine the categorization of the land cover in the Swat basin.

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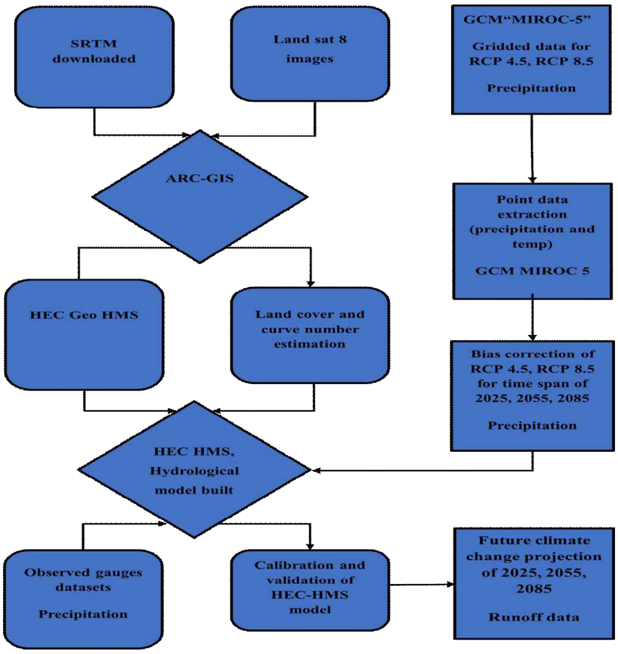

Figure 2. Methodological Flow chart

C. Hydrological Model Performance Indicators

To assess efficiency and performance, three performance indicators are used: the Nash-Sutcliffe coefficient (NS), the coefficient of determination (R2), and the RMSE. Below is a detailed discussion of each performance indicator.

1) Coefficient of Determination (R^2)

R is the symbol for this statistic performance indicator. This demonstrates how well the model's simulated runoff values accurately mirror the variation in observed runoff values. The correlation square between observed and simulated values is also known as the coefficient of determination. The coefficient of determination might be anywhere between 0 and 1. The coefficient of determination's mathematical equation is:

$$R^2 = \frac{\sum\left(Qobs - \overline{Qobs}\right) \times \left(Qsim - \overline{Qsim}\right)}{\sqrt{\sum\left(Qobs - \overline{Qobs}\right)^2 \times \left(Qsim - \overline{Qsim}\right)^2}} \qquad \text{Equation .1}$$

Where Qobs denotes observed runoff and Qsim denotes simulated runoff values, (Qobs) denotes the mean of observed values and (Qsim) denotes the mean of simulated runoff values, respectively.

2) Nash-Sutcliffe Coefficient (NSE)

It's a statistic coefficient that compares the observed data's variance to the simulated data's variance. This is signified by NSE and determines the model's ability to predict [14]. The model's efficiency is determined by how well the model's simulated data matches the observed data. The Nash-Sutcliffe efficiency equation is as follows:

$$NSE - 1 - \frac{\sum(Qsim - Qobs)^2}{\sum(Qobs - \overline{Qobs})^2} \qquad \text{Equation.2}$$

Where Qsim denotes simulated discharge values, Qobs denotes observed discharge values, and (Qobs) denotes the average values of the observed values.

D. Hydrological Analysis

We have selected an experimental method for our research study based on the HEC-HMS Hydrological model to explore the required objective. This is a standard method for analysing and exploring the evidence by employing various systematic steps to obtain the desired results [15].

1) Modelling Setup

There are several methods to compute different hydrological process in HEC-HMS [16]. Each of them gives different statistical performance which depends on available data and requirement of the project but for swat catchment SCS (Soil Conservation Service) loss method is considered as suitable choice. For initial and constant losses, constant monthly for base flow, and SCS unit hydrograph for transformation, the SCS unit hydrograph and Muskingum routing technique were determined to be the best [17].

2) Calibration and Validation

Flow observations were used to calibrate and validate the model on daily basis. The calibration time for the study was 2005-2010, while the validation period was 2011-2015 [18]. In table I below we have provided the Model parameters to be calibrated.

TABLE I
MODEL PARAMETER WITH THEIR CALIBRATION RANGE

Parameters	Calibration
PX temperature (C)	1.0 to 1.2
Base temperature(C)	0.9 to 0.95
Lapse rate (DEGREE C/100 m)	-0.65 to -0.45
Degree day factor (mm /C DAY)	1 to 1.7
Impervious (%)	3 to 5
Initial abstraction (mm)	4
Muskingum K(hr.) and X	1.5 to 2.5 and 0.2 to 0.3
Curve number	44 to 69

IV. RESULTS

A. Hydrological modelling (HEC-HMS)

The strategies are employed in the HEC-HMS model for the best calibrated values of parameters in this research study. SCS curve number for loss method, SCS unit hydrograph method for transformation technique, constant monthly base flow method for base flow data, and Muskingum routing method for river routing are the details of the methods chosen for the best simulation of the model. Because the Swat River Basin has permanent glaciers, it is also necessary to obtain calibrated values for temperature-related factors, for which the temperature index approach is employed. PX temperature, base temperature, lapse rate, and Meltrate function are the parameters.

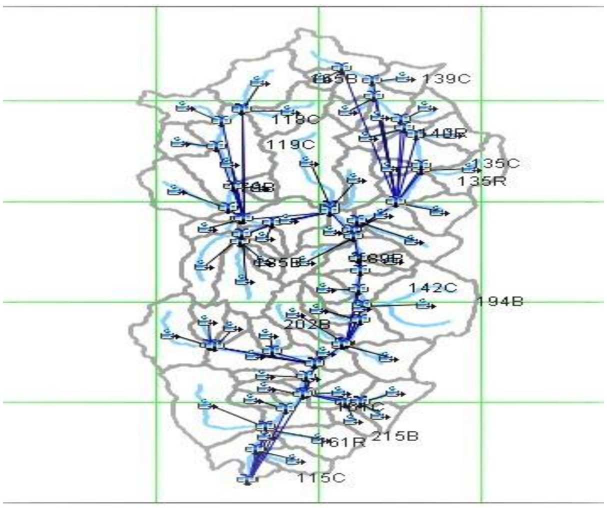

Figure 3. Sub-basins of Swat River catchment

The final calibrated parameters assigned to the sub basin of the watershed for the HEC-HMS model are shown in the table II.

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Table II
Calibrated Parameters

PARAMETERS	CALIBRATION OF VALUES
Initial abstraction (IN)	1-4 mm
Curve Number	44-69
PX Temperature	1-2 Degree Centigrade
Base Temperature	0.9 Degree Centigrade
Lapse Rate	-0.65 to -0.45 Degree C/100 m
Degree Day Factor	1 to 1.7 mm /C DAY
Impervious	3 to 5 percent
Muskingum X and K	0.2 to 0.3 and 1.8 to 2.5hr

B. Statistical Evaluation

Statistical analysis yields positive outcomes. On a daily scale, performance indicators are within acceptable limits. For calibration and validation, the Nash-Sutcliff coefficient (NSC) is determined to be 0.84 and 0.812, respectively, the Root Mean Square Error (RMSE) for calibration and validation was 5.5 and 2.8, respectively. The coefficient of determination R2 for calibration and validation is 0.86 and 0.84, respectively. For calibration and validation, the graphs in figure 4 and 5 represents observed and HEC-HMS daily discharges. Almost for both periods where is, the HEC-HMS model copies the patterns of low and high peaks. Although the HEC-HMS outcomes are overstated, there is a good connection between observed and simulated results in general.

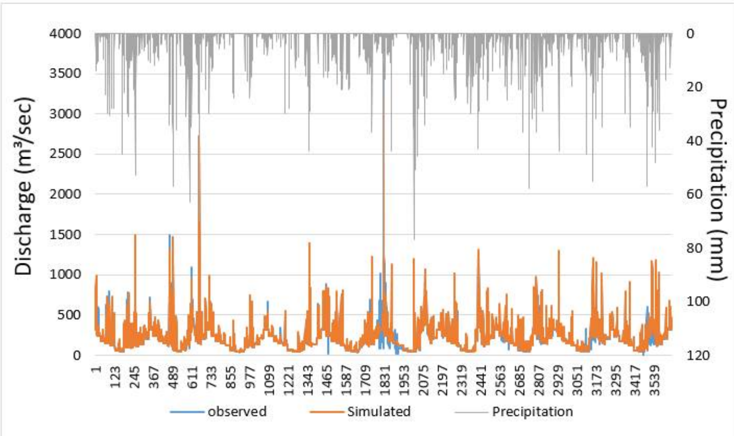

Figure 4. Comparison of Observation and Simulated values, after calibration

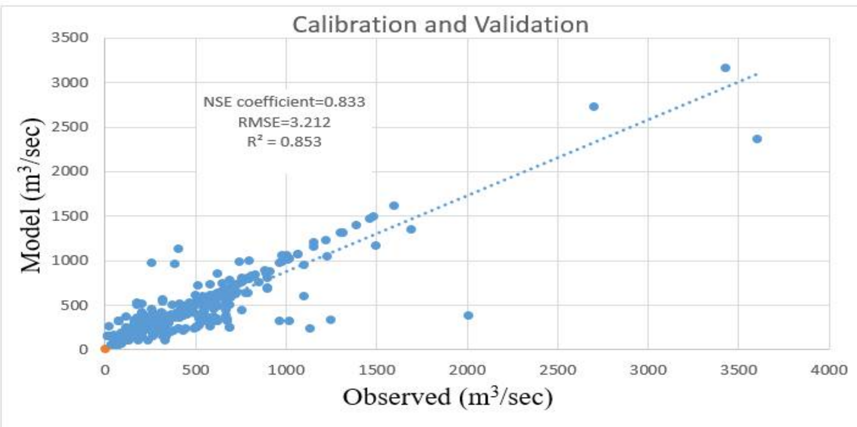

Figure 5. Scattering chart of Observed and Model Stream flows

C. Statistical Evaluation on Seasonal Scale

Statistical evaluation of model on seasonal scale has been carried out and shown in table III below. The season intervals are defined by winter (Nov- Feb), spring (Mar- Apr), summer (May-Jun), Monsoon (Jul- Aug) and autumn (Sep- Oct). The performance of the model to simulate flows in spring season is low as compared to the other seasons but the results lie in acceptable range. July and August as usual are the wet months and peak flows occur in this season. The model performance is overall in acceptable range.

Table III
Statistical Performance Evaluation On Seasonal Scale

Time (season)	NSE		RMSE		R^2	
	Calibration	Validation	calibration	Validation	calibration	validation
Winter (Nov-Feb)	0.82	0.86	2.35	3.70	0.84	0.88
Spring (Mar-Apr)	0.81	0.78	3.31	4.17	0.72	0.69
Summer (May-June)	0.87	0.81	1.43	1.09	0.72	0.81
Monsoon (Jul-Aug)	0.82	0.83	2.27	2.54	0.87	0.82
Autumn (Sep-Oct)	0.79	0.83	3.63	4.54	0.91	0.85
Annual	0.84	0.81	2.75	1.69	0.86	0.83

D. Climate Change Impacts

Future climate change analysis was carried out using MIROC5-GCM (Global Circulation Model) model, the flow and precipitation series was extended over century. To investigate the climate implication with respect to time, series was categories into 3 intervals from (2011-2040) as Early Century, (2041-2070) as Mid Interval and (2071-2100) as Late Interval.

1) Bias Correction

To match historical baseline data and future anticipated datasets to baseline data, bias correction is used. The monthly bias correction factors are created from formulas utilizing the reference dataset and observed baseline dataset, and then applied to MIROC5 datasets of RCP 4.5 and RCP 8.5 future predicted data.

2) Precipitation

Precipitation is one of the main parameters which drives the hydrological cycle in basin. It is also influence by temperature and other climate variables. Now considering this, one can notify the importance of this variables which can be greatly sensitive towards changing environment. In our study we have carried out climate change analysis over precipitation so to investigate the variation in quantity and shift in seasons. Seasonal deviations of precipitation at each interval of century are provided in table IV below. Seasonal deviation of early interval shows maximum growth in winter season in case of both RCP4.5 and RCP8.5, while precipitation seems decrease in autumn season. At Mid Century, positive trends of both RCP4.5 and RCP8.5 remain similar, as precipitation in winter seems to grow, however, in summer and monsoon precipitation seems to drop down. Analysis of late century demonstrate that for RCP 8.5, winter and monsoon season seem to provide larger positive variation. In the case of RCP4.5 winter seasons have showed higher positive values, but summer showed decline. In the end, analysis seems to project higher winter precipitation while other seasons remain somewhat random. Monthly variation in precipitation by RCP4.5 and RCP8.5 with respect to baseline is provided down in table IV below. RCP8.5 predicts rise in precipitation in April during in all time. February, May, July, August, November, and December also showed rise in intensity in late century, while September remains low for 2025. Analysis of RCP4.5 predicts, little change except relatively high precipitation was observed during the month of May except for 2055.

3) River Flow

Change in pattern of precipitation and temperature variables over the time due climate change might directly influence the flow of river. Therefore, future analysis must be prepared to overview the variations along the time. Investigation will classify the analysis into monthly and seasonal based. While study is also distributed in terms of century intervals. Results of seasonal analysis of Swat River is provided down below in table IV and V below. For Early Century, analysis showed higher deviation during monsoon and autumn season for both RCP4.5 and RCP8.5. RCPs during Mid Century showed higher variation in monsoon and autumn as compared to early century. Further late century also showed similar trends.

TABLE IV
Baseline Flows Seasonal Wise

Baseline (1980-2005)	Stream Flow (cumecs)
Winter (Nov-Feb)	278.2641
Spring (March-April)	181.12
Summer (May-Jun)	1175.3
Monsoon (Jul-Aug)	1086.6
Autumn (Sep-Oct)	691.9862
Annual	3413.27

Monthly variation in flows by RCP4.5 and RCP8.5 with respect to baseline is tabulated in table V below. Both of scenarios have predicted higher future flows, but among them RCP 8.5 have showed higher quantities of water as corresponding to baseline and RCP4.5. All time higher quantities in both RCPs shown by July. However, Study also showed January and February months with less variation as comparison to absolute baseline values. Monthly variations are provided below in figure 6, 7, and 8.

TABLE V
Seasonal And Annual Flow Deviations by RCP4.5 and RCP 8.5

Century-Intervals	Season	Flows (cumecs)			
		RCP 8.5		RCP 4.5	
		Absolute	Deviation	Absolute	Deviation
EARLY	Winter	459.6	181.4	457.0	178.7
	Spring	348.6	167.5	345.0	163.9
	Summer	1298.2	122.9	1292.0	116.7
	Monsoon	1995.4	908.8	1300.0	213.4
	Autumn	1231.3	539.3	750.0	299.7
	Annual	4588.2	1174.9	4144.0	972.4
MID	Winter	544.0	265.7	435.2	157.0
	Spring	392.0	210.8	395.0	213.9
	Summer	1404.1	228.8	1410.2	234.9
	Monsoon	2093.4	1006.8	1720.5	633.9
	Autumn	1783.2	1091.2	1139.7	689.4
	Annual	6216.7	2803.4	669.3	1929.0
LATE	Winter	575.5	297.2	497.2	218.9
	Spring	406.6	225.5	405.7	224.5
	Summer	1467.4	292.1	1465.5	290.2
	Monsoon	2151.1	1064.5	1837.5	750.9
	Autumn	1360.0	668.0	1160.0	709.7
	Annual	5960.6	2547.4	5365.8	2194.2

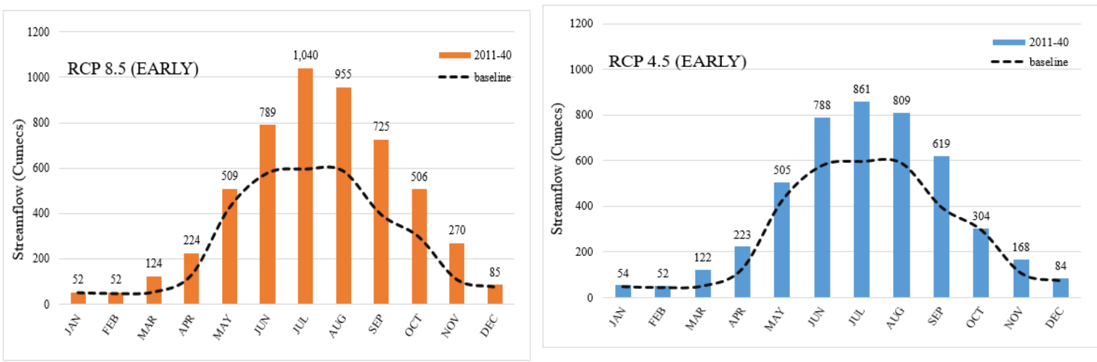

Figure 6. Monthly Flow of RCP4.5 and RCP8.5 at Early Century

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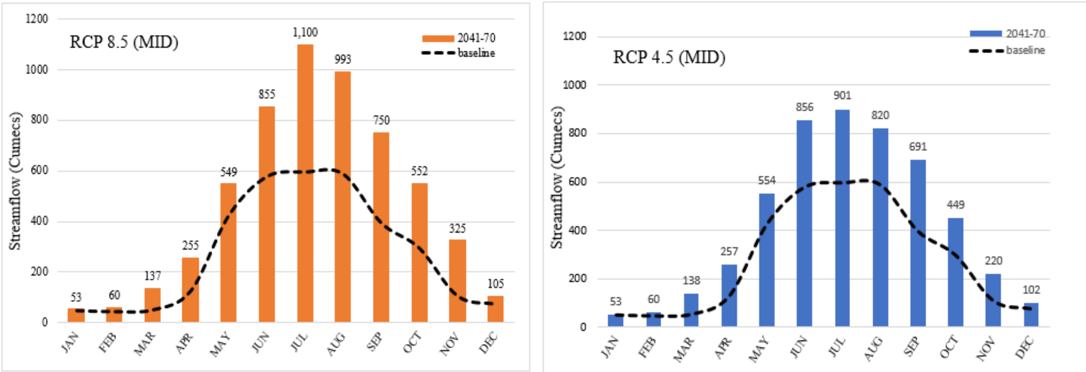

Figure 7. Monthly Flow of RCP4.5 and RCP8.5 at Mid Century

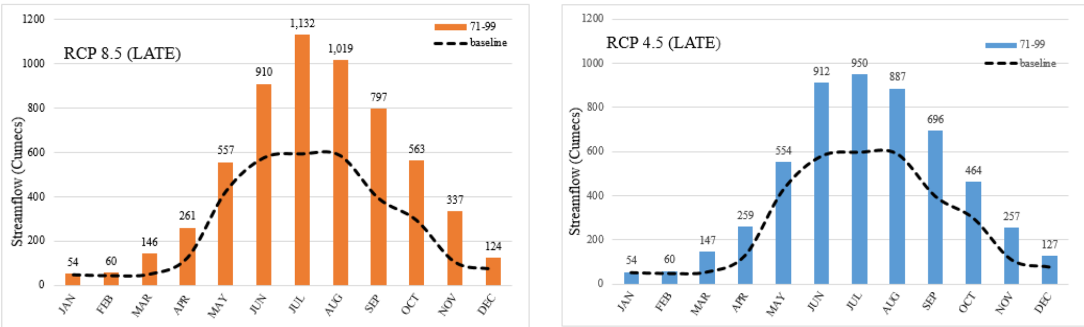

Figure 8. Monthly Flow of RCP4.5 and RCP8.5 at Mid Century

V. CONCLUSION

Climate change is considered one of the threats to a sustainable global environment. Intense global warming can introduce extreme characteristic to local eco-system, thereby it needed clear understanding. Fortunately, with modern progress in the field of computation one can simulate such phenomena, by developing hydrological models. For the study we have simulated swat river basin up to the confluence at KhawazaKhela in HEC-HMS model. Due to limitation of climate data only kalam station was used to incorporate as weather input. On a daily scale, the Model's performance metrics are within acceptable limits. For calibration and validation, the Nash-Sutcliff Coefficient (Ns) is determined to be 0.84 and 0.812, respectively. For calibration and validation, the Root Mean Square Error (RMSE) was 5.5 and 2.8, respectively. For calibration and validation, the coefficient of determination (R2) is 0.86 and 0.84, respectively. Effects of Climate Change on precipitation and stream flows were also studied, using climate scenarios of RCP4.5 and RCP8.5 by MIROC 5 GCM. For this purpose, future precipitation was prepared by extracting future precipitation from MIROC at Kalam station and applying linear bias correction with observed values. Resultant is then input into the model. Seasonal and monthly variation in stream flow and precipitation were noted. Future analysis of precipitation showed an increase in precipitation for both RCPs. At the end of century total annual rise of +195mm (14.8%) was observed for RCP8.5 and 119mm (9%) was observed for RCP4.5. Seasonal analysis showed, rise in winter precipitation in all RCPs, however, other seasonal showed random trend. RCP8.5 predicts rise in precipitation in April during in all time. February, May, July, August, November and December also showed rise in intensity in late century, while September remains all-time low except for Mid-century. Analysis of RCP4.5 predicts little change except relatively high precipitation was observed during the month of May except for Mid-century. Analysis seems to predict higher magnitudes of flow in future, at the end, RCP4.5 suggest 38.9% increase in flows and RCP8.5 showed 40.9% increase in flow. Seasonal analysis conducted on RCP8.5 seems to suggest higher deviation up to (908.8, 1091.2 & 1064.5) cumecs during Early, Mid and Late intervals. In the case of RCP4.5, (299.7, 689.4, and 750.9) cumecs are recorded as higher deviation at 3 intervals of century. These highest deviations are recorded during the season of Monsoon and autumns. On the other hand, monthly analysis showed peak variations in the month of July for both RCPs. As a whole stream flow projection has shown, RCP8.5 to be quantitatively high as compared to RCP4.5.

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