INTEGRATED CLIMATE ADAPTATION AND DISASTER RESILIENCE ASSESSMENT OF CRITICAL INFRASTRUCTURE ASSETS IN KP

Hydrology Report

May 2023

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Executive Summary

Conventionally, hydrological studies for planning and design of infrastructure systems were based on historical datasets. However, in the wake of climate change, this approach is no longer valid and needs to be replaced with projections made while accounting for climate change impacts.

Climate change based modelling of hydrological phenomena involves: selection of appropriate Shared Socio-economic Pathways (SSPs) – SSPs are global greenhouse gas emission scenarios pertaining to different climate policies; selection of General Circulation Models (GCMs) that are suitable for the study purpose and appropriate for the study area – GCMs are computer driven models used for projecting climate change; downscaling the selected GCMs to a resolution that is useful for getting climate variables (temperature and precipitation) corresponding to specific project sites; using the projected climate variables for deriving stream flow values at selected control station(s); and finally based on the same stream flow values, estimating floods magnitudes corresponding to various return periods.

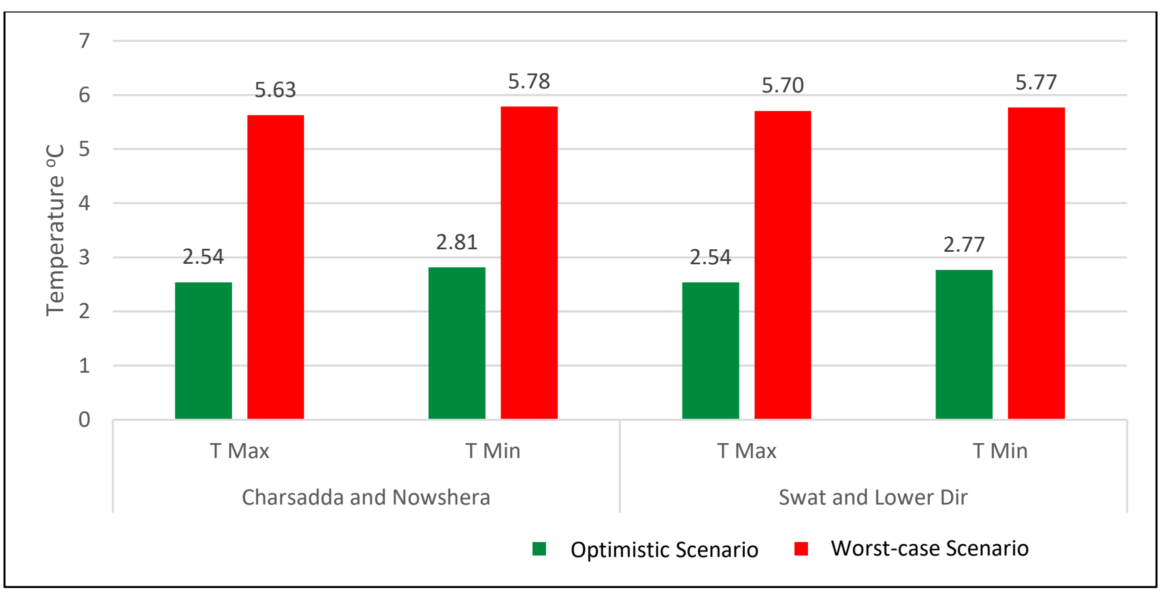
In this study Word Bank Knowledge Portal (WBKP) for climate change was also used to acquire the predicted climate variables of temperature and precipitation for comparison with the models used for this study. The WBKP provides mean monthly decadal variations in temperature and precipitation based on multi-modal ensemble of GCMs for different SSP scenarios for Pakistan. Due to very low resolution of data, both spatial and temporal resolutions, the data could not be used for the purpose of this study. However, the data was used for comparison with the trends in temperature and precipitation predicted by ensemble of GCMs in this study. The comparison showed a close agreement between the two datasets, providing confidence for the use of the selected GCMs for the study area.

For this study climate data (minimum and maximum temperatures and precipitation – daily data) obtained from Pakistan Meteorological Department (PMD) and daily flow data obtained from WAPDA was used. Both the climate and flow data of 30 years (1993-2022) was used in this study.

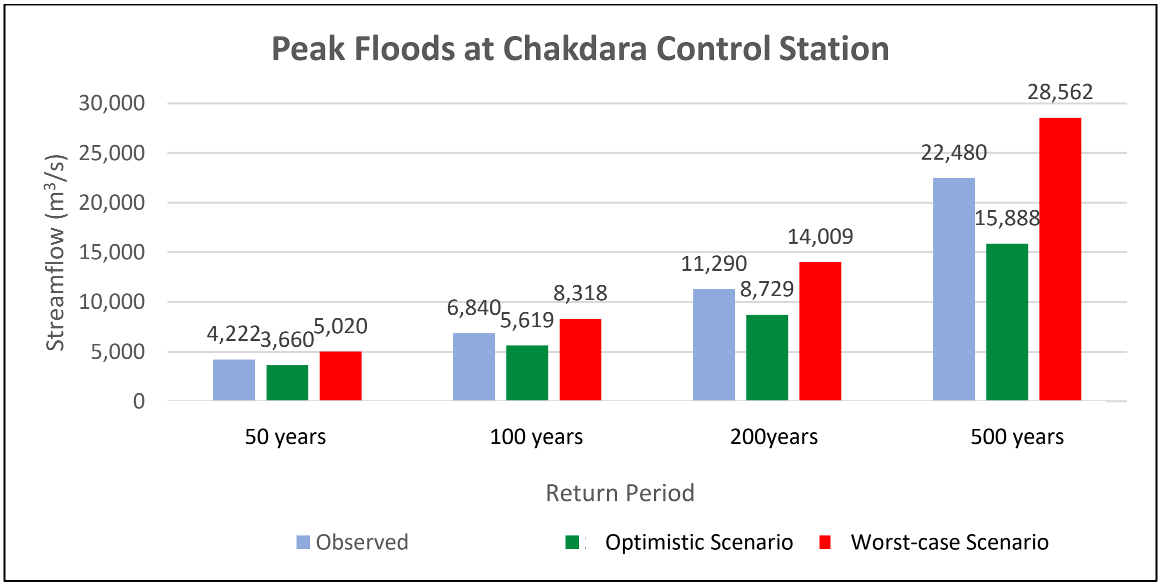
In this study individual project sites are scattered over the districts Swat, Lower Dir, Charsadda and Nowshera. Two SSPs were selected to run GCMs, SSP245 and SSP585. For simplicity the former has been called an optimistic scenario while the latter as the worst-case scenario in this report. An ensemble of best suited GCMs out of 11 GCMs were used for the study area.

For the Swat and Lower Dir region, the rise in maximum temperature is projected to be 2.77 °C and 5.77 °C under SSP245 (Optimistic) and SSP585 (Worst-case) scenarios respectively, by the end of the century. Similarly, an increase in the minimum temperature is projected to be 2.53 °C and 5.70 °C under SSP245 (Optimistic) and SSP585 (Worst-case) scenarios respectively, over the same period.

For the Charsadda and Nowshera regions, the rise in maximum temperature is projected to be 2.81 °C and 5.78 °C under SSP245 (Optimistic) and SSP585 (Worst-case) scenarios respectively, by the end of the century. Similarly, an increase in the minimum temperature is projected to be 2.54 °C and 5.62 °C under SSP245 (Optimistic) and SSP585 (Worst-case) scenarios respectively, over the same period.



The projected 100-year return period flows at the project locations are expected to increase by 22% under the SSP585 (Worst-case) scenario and the same for 200-year return period are expected to increase by 24%.



This study revealed that in past decades, as obvious from the comparison of historic and Optimistic Scenario, the flow of the Optimistic Scenario has already been surpassed and therefore in planning and designing of major critical infrastructure Worst-case Scenario needs to be considered.

It is clear from the results presented above that climate change impacts are not trivial and therefore must be properly considered for the planning and design of infrastructure systems. Such an approach would help improve society's resilience against climate change induced hazards.

1 Methodology

The methodology adopted in this project is briefly outlined in the flow chart shown in Figure 1-1. Each of the steps is further elaborated in the subsequent sections.

Figure 1-1: Flow chart illustrating the methodology of the project.

1.1 Data Collection

For this study, three main types of data were required. The details about the type of data and their sources are described below:

1.1.1 Climate Data

Climate data that was required in this study includes minimum temperature, maximum temperature, and precipitation on daily basis for at least 30 years.

Pakistan Meteorological Department (PMD) maintains its weather station across the country, and they provide the data on payment. The location of PMD stations is shown in Figure 1-2.

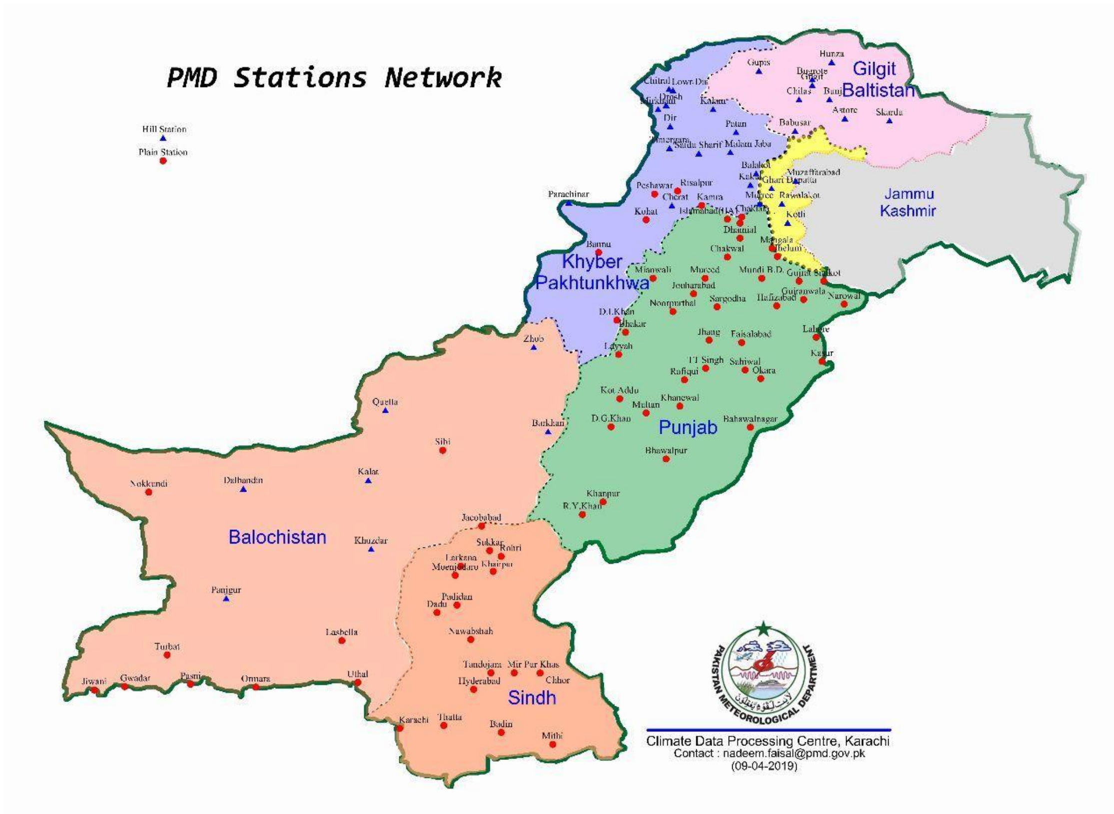


Figure 1-2:PMD Weather Stations in Pakistan[1] (Source: Pakistan Meteorological Department)

There are numerous online sources from where the required climate data could be obtained. Some of these sources are Global Weather Data, NOAA.

Daily data of minimum temperature, maximum temperature and precipitation for the following two stations was obtained from PMD:

- Peshawar (1993-2022),
- Saidu Sharif (1993-2022) and

1.1.2 Discharge Data

Discharge data was required for the purpose of calibration/validation of the precipitation-runoff model. Daily discharge data of gauging station with the catchment, where the point of interest/study is located, was needed.

[1] http://www.pmd.gov.pk/cdpc/home.htm

WAPDA in all over Pakistan and Irrigation Department KP in KP maintains gauging stations at various streams within their territorial jurisdictions.

Flow data was obtained for Chakdara from WAPDA from 1993 to 2022. However, some data was missing during the period from July 29, 2010 till Oct 26, 2010. This data was probably not available as the gauge suffered damage in the 2010 floods. Consequent data was available after re-installation of the gauge in October 2010. This data was extremely important due to two reasons. Firstly, continuous data is mandatory for running the hydrological model while the second reason is that the model might underestimate the discharge in absence of the important extreme event of the 2010 floods.

Fortunately, the discharge data at Munda, a station downstream of Chakdara station, was available for the missing period. Also, data of 2009 for the whole year was available. The daily flow of 2009 was plotted for Munda and Chakdara that is shown in the Figure 1-3. A perfect correlation with R Square as 1 was found between the two data points. The relation between the flow is expressed by the following equation:

$$Flow\ at\ Chakdara = 0.77 \times Flow\ at\ Munda + 6.6278$$

Using the above equation, data at Chakdara was calculated for the missing period.

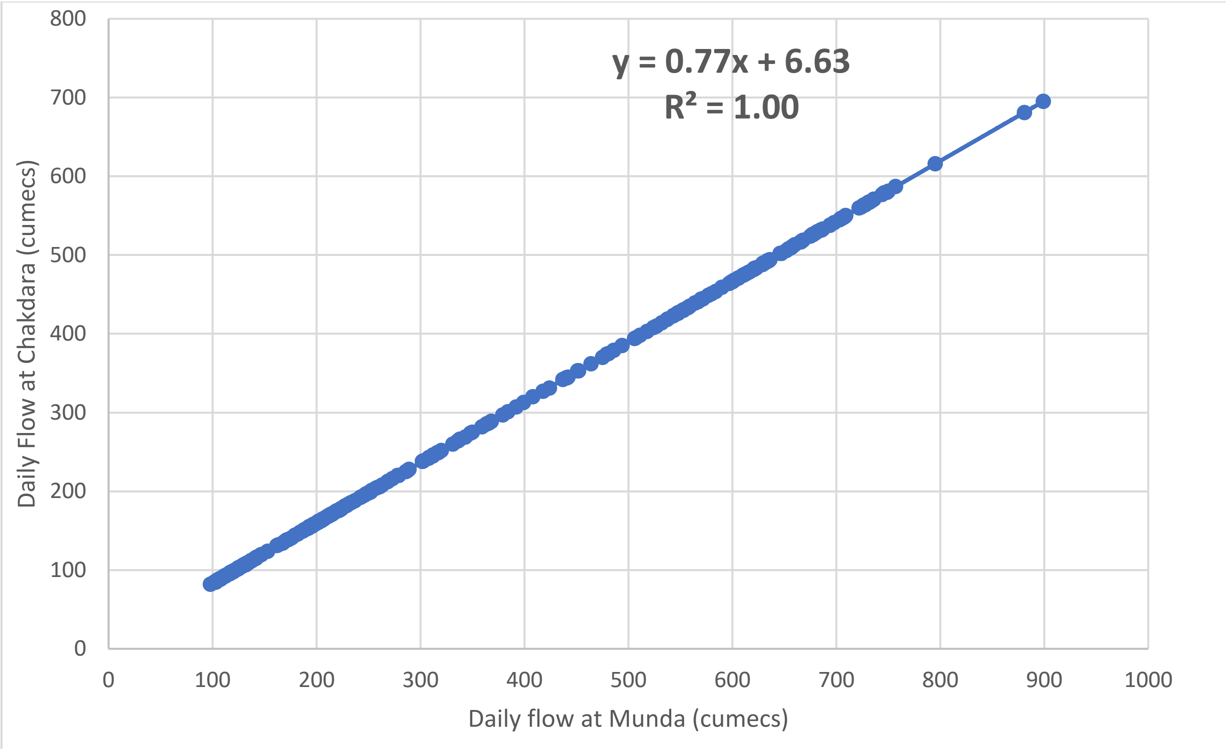


Figure 1-3: Daily flow at Munda vs Daily flow at Chakdara

1.1.3 Terrestrial Data

Digital elevation model (DEM) data of the study area was downloaded from Shuttle Radar Topography Mission (SRTM). Its resolution is 30 m x 30 m. DEM data is used for watershed delineation. Figure 1-4 and Figure 1-5 demonstrate the project location and the delineated watersheds respectively.

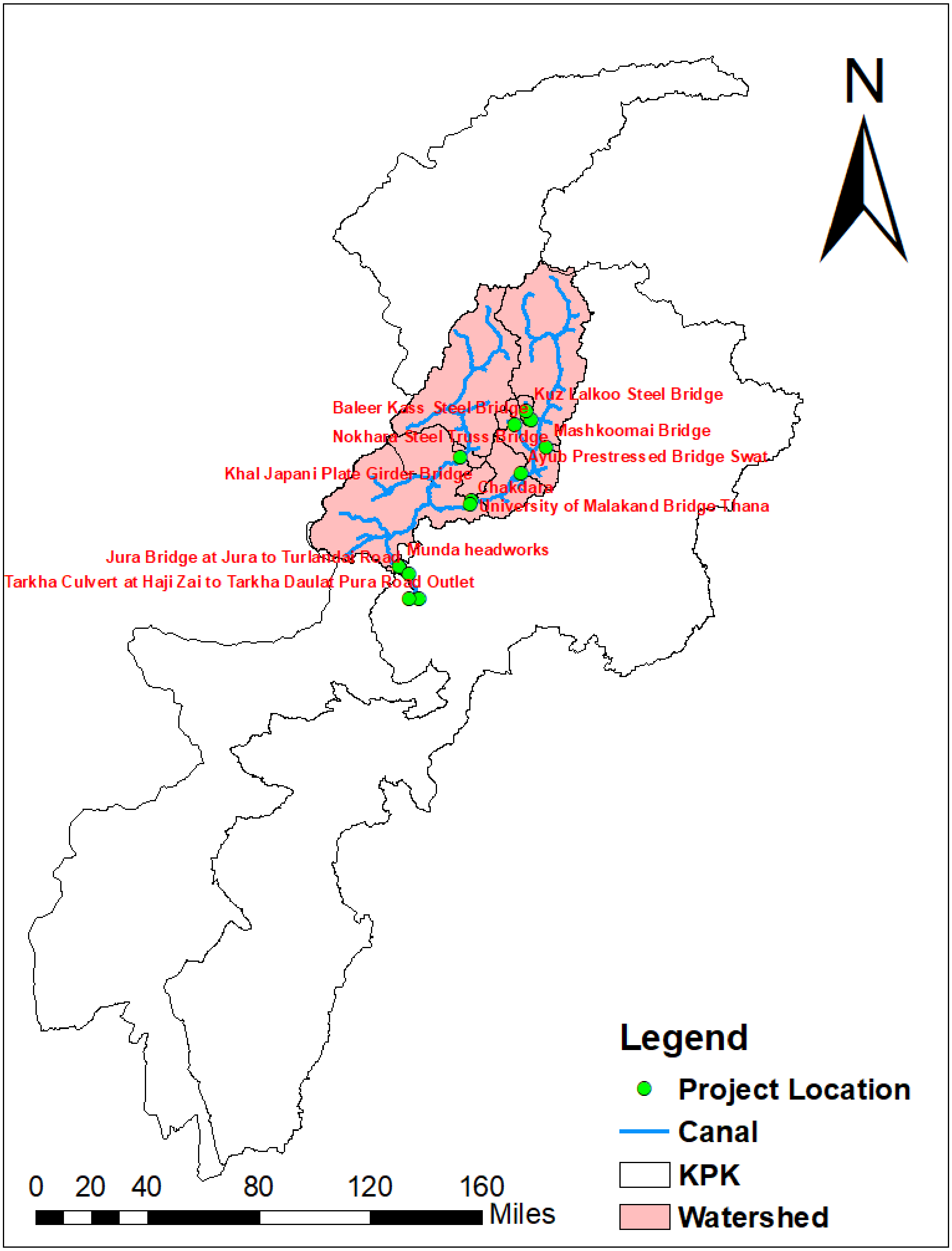


Figure 1-4: Overview of project locations

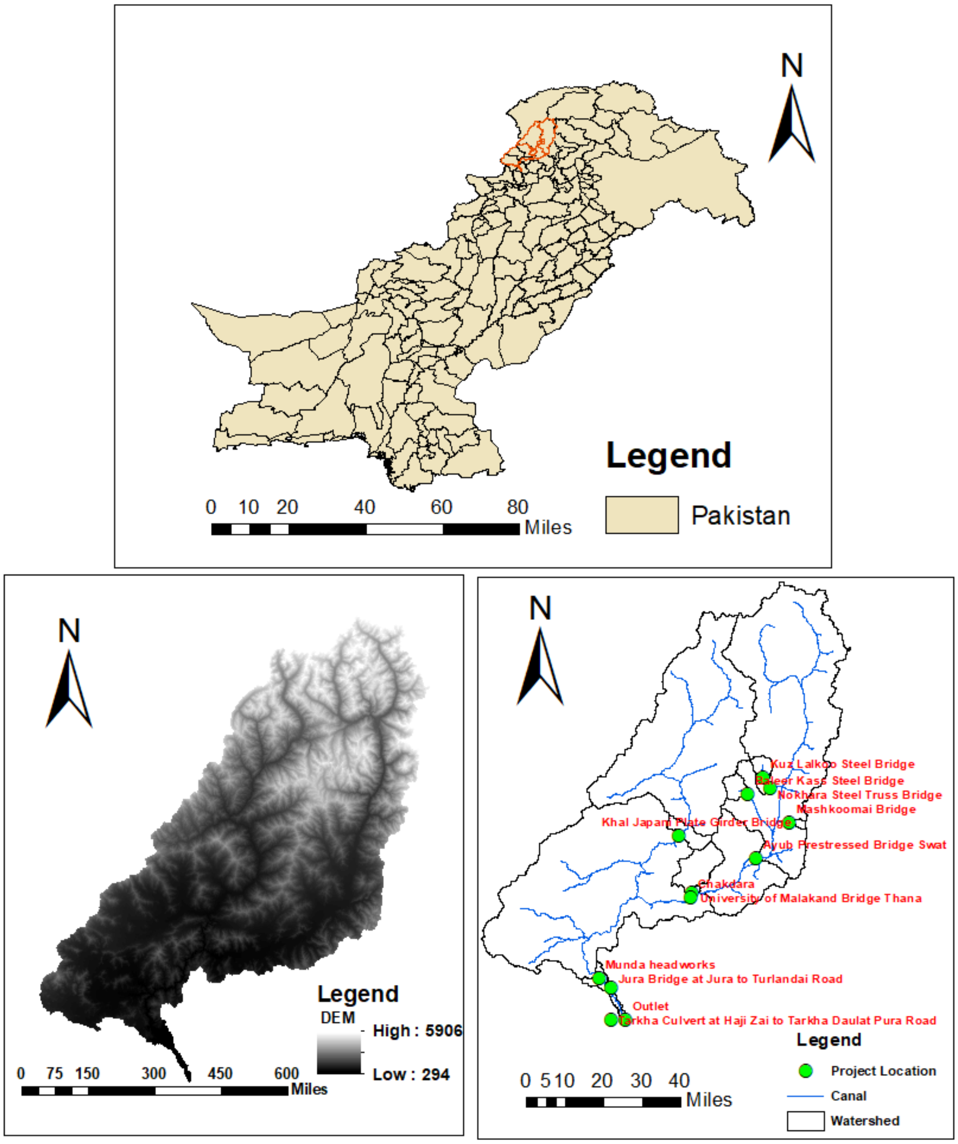


Figure 1-5: Overview of delineated watersheds

Land use data of European Space Agency (ESA) Sentinel-2 imagery having 10m resolution was downloaded from Impact Observatory, Microsoft, and Esri. The details of land use classes for the delineated watershed are demonstrated by Figure 1-6.

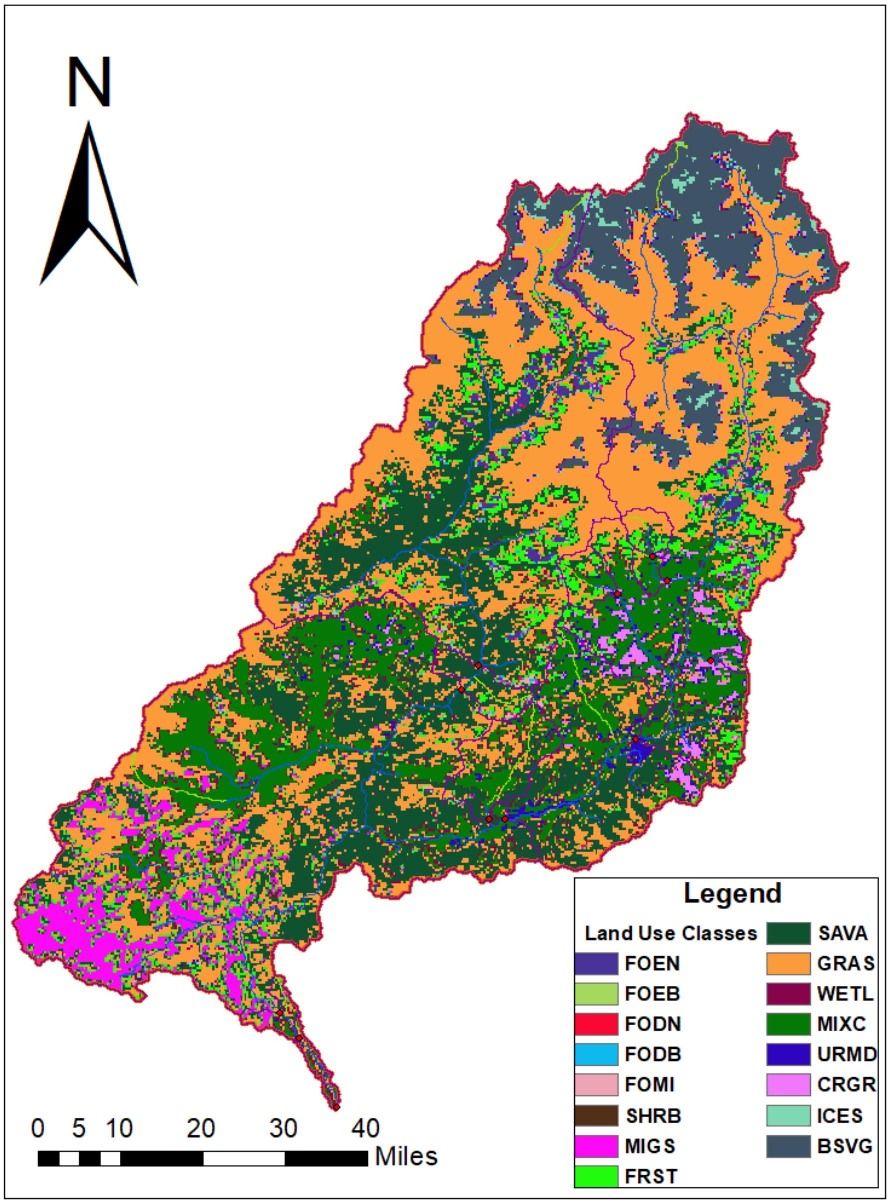


Figure 1-6: Details of the land use classes for the delineated watersheds

Soil data was downloaded from the Food and Agriculture Organization (FAO). The details of soil classes for the delineated watershed are demonstrated by Figure 1-7.

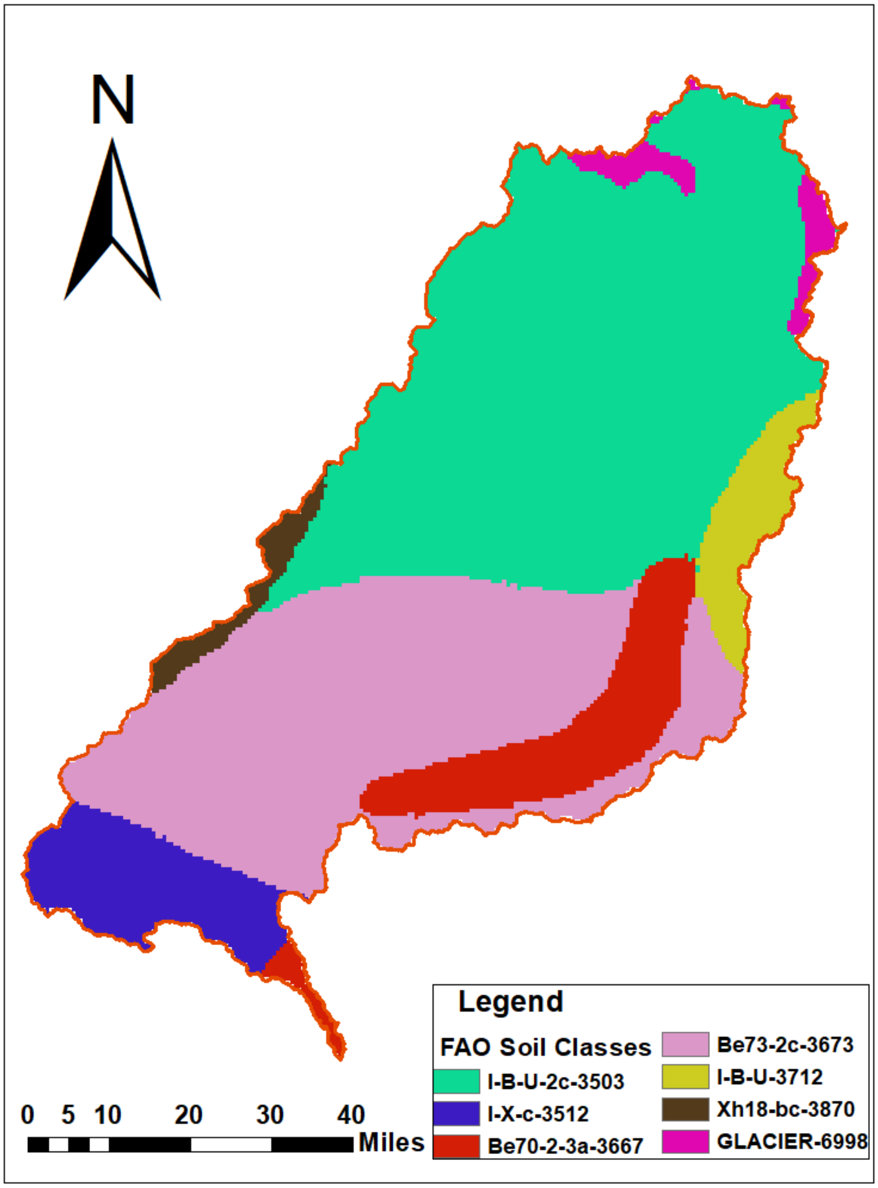


Figure 1-7: Details of the soil classes for the delineated watershed

1.1.4 GCM Models Data

Daily precipitation and temperature (minimum and maximum) data of 10 GCMs were used for futuristic streamflow predictions[2] whose details are provided in Table 1-1. These models were obtained from CMIP6 archive.

[2] Karim, R., Tan, G., Ayugi, B., Babaousmail, H., Liu, F., 2020. Evaluation of historical CMIP6 model simulations of seasonal mean temperature over Pakistan during 1970–2014. Atmosphere 11, 1005.

Table 1-1 : Demonstrates GCMs horizontal resolution and vertical levels

Model	**Horizontal Resolution**	**Vertical Levels**
NESM3 (China)	~1.1 degrees (~110 km)	60
CMCC-ESM2 (Italy)	~0.25 degrees (~25 km)	56
CNRM-CM6-1 (France)	~0.25 degrees (~25 km)	91
CNRM-ESM2-1 (France)	~1.4 degrees (~140 km)	91
EC-Earth3-Veg-LR (Europe)	~0.75 degrees (~75 km)	91
GFDL-ESM4 (USA)	~0.25 degrees (~25 km)	33
INM-CM4-8 (Russia)	~2.5 degrees (~250 km)	20
INM-CM5-0 (Russia)	~1.5 degrees (~150 km)	40
MIROC6 (Japan)	~1.4 degrees (~140 km)	80
MRI-ESM2-0 (Japan)	~1.1 degrees (~110 km)	80

1.2 Meteorological Parameters Projection

Global climate models (GCMs) are used to project meteorological parameters such as temperature, precipitation, humidity, wind speed, and atmospheric pressure. GCMs are complex computer models that use mathematical equations to simulate the physical processes of the atmosphere, oceans, and land surface.

The projections of meteorological parameters based on GCMs are highly dependent on the scenario used for emissions of greenhouse gases (GHGs) and other factors that affect the climate. Therefore, GCMs are used in conjunction with emissions scenarios to provide a range of possible future climate conditions.

One commonly used emissions scenario is the Coupled Model Intercomparison Project Phase 6 (CMIP6) framework, which includes different scenarios that represent different levels of GHG concentrations in the atmosphere by the end of the 21st century. The current project is based on two CMIP6 scenarios i.e., SSP245 and SSP585 using Multi-model Ensemble (MME) approach.

1.2.1 Multi-model Ensemble (MME)

Ensemble computation of GCMs is a common technique used to improve the accuracy of climate predictions. In the present project the performance of GCM ensembles was computed using Taylor skill score (TSS) and rating metric (RM) technique[3].

In this project, the best performed GCMs (among 10 CMIP6 GCMs) were identified using the following two steps: (a) Taylor skill score (TSS) calculation and (b) rating metric (RM) computation. First, TSS was calculated for precipitation (P), temperature maximum (Tmax), and temperature minimum (Tmin) by comparing the GCM's output with PMD observed data for 1993–2022 as given in Equation (1.1):

$$S = \frac{4(1+R)^4}{(\sigma+\frac{1}{\sigma})^2(1+Ro)^4} \qquad (1.1)$$

where R is the Pearson correlation coefficient between GCM output and observed data, σ is the ratio of the standard deviation of GCM output to the standard deviation of observations, and R0 is the maximum possible value of the correlation coefficient, which is equal to 1. The TSS varies from 0 to 1, where a value closer to 1 was considered as the best-performed model for the given region.

Similarly, the RM as given in Equation (2) was computed individually for P, Tmax, and Tmin for each GCM, based on the rank obtained from TSS. Subsequently, the overall rank of the GCMs were computed based on the average RM value of P, Tmax, and Tmin. Similar to TSS, the RM ranges 0 to 1, where a value closer to 1 indicates good performing GCMs and a value closer to 0 indicates poorly performing GCMs,

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[3] Dey, Aiendrila, Debi Prasad Sahoo, Rohini Kumar, and Renji Remesan. "A multimodel ensemble machine learning approach for CMIP6 climate model projections in an Indian River basin." *International Journal of Climatology* 42, no. 16 (2022): 9215-9236.

$$\text{RM}= 1 - \frac{1}{n}\sum_{i=1}^{n} Ranki \ldots\ldots\ldots\ldots\ldots\ldots..(1.2)$$

where n is the number of CMIP6 GCMs and i is the rank of the individual GCMs based on the TSS

1.2.2 Bias Correction of GCMs

Bias correction is a statistical technique that is commonly used to adjust the output of GCMs to better match observed data. GCMs are complex computer models that use mathematical equations to simulate the physical processes of the atmosphere, oceans, and land surface. Despite their sophistication, GCMs have limitations and can produce biases, or systematic errors, that can affect their accuracy in simulating present and future climate conditions.

Bias correction techniques involve comparing the output of GCMs with observed data for a particular variable, such as temperature or precipitation. Statistical methods are then used to adjust the GCM output to match the observed data, often by applying a linear or nonlinear transformation to the simulated values.

Climate Model data for hydrologic modeling (CMhyd) is a Python-based tool which enable the use of global and regional climate model data in hydrological models. It applies temporal and spatial bias correction of climate model data, so it can best represent the observation gauges used as inputs for hydrological models. CMhyd tool includes several biasing methods such as linear scaling (additive and multiplicative), temperature variance scaling, precipitation power transformation, precipitation local intensity scaling, delta change correction (additive and multiplicative), and precipitation and temperature distribution mapping. Linear scaling (additive and multiplicative) and delta change correction (additive and multiplicative) bias correction approaches[4] were used for the

[4] Haleem, K., Khan, A.U., Ahmad, S., Khan, M., Khan, F.A., Khan, W. and Khan, J., 2022. Hydrological impacts of climate and land-use change on flow regime variations in upper Indus basin. *Journal of Water and Climate Change*, *13*(2), pp.758-770.

current study. The model accuracy was assessed through several statistical indicators i.e. Nash-Sutcliff Efficiency (NSE), Coefficient of Determination (R^2), and Ratio of Root Mean Square Error (RRMSE) and Standard Deviation (RSR). Flowchart demonstrates the bias correction of historic and futuristic GCMs data as demonstrated by Figure 1-8.

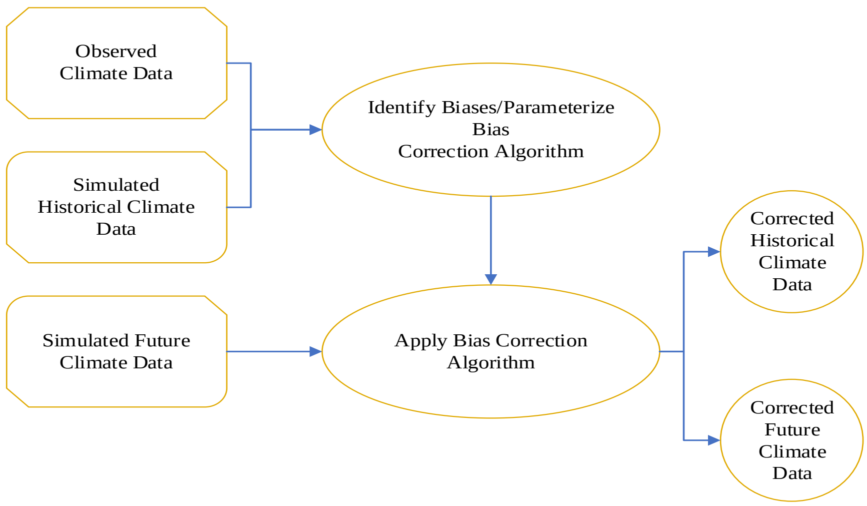

Figure 1-8: Flowchart demonstrating bias correction of GCMs data

1.2.3 Anomaly Detection of Meteorological Parameters

To detect anomalies in climate models, one simple technique is to use a statistical method called "anomaly detection." An anomaly is the difference between the mean of decadal average values of climatic parameters to the average observed data historical record (base line). Here are the steps to perform anomaly detection on climate model data:

- Collect the observed data and use it as a reference period. This reference period should be a time period that is considered "normal" or representative of the climate in the region of interest. Compute the mean of reference period.
- Split the climatic parameters data into decades and compute each decade mean. Calculate the difference between the mean of decadal average values of climatic parameters to the average observed data historical record (base line).

1.3 Streamflow Computation

1.3.1 SWAT Model description

The Soil and Water Assessment Tool (SWAT) is a comprehensive, semi-distributed hydrological model used to simulate the impact of land management practices and climate change on water resources, nutrient cycling, and sediment transport in watersheds. The model was developed by the United States Department of Agriculture (USDA) Agricultural Research Service and is widely used around the world for water resources management, agricultural planning, and environmental impact assessment.

SWAT simulates the hydrological cycle by dividing a watershed into multiple sub-watersheds, each of which is further divided into hydrologic response units (HRUs) based on land use, soil type, and other physical characteristics. The model incorporates various processes such as rainfall-runoff, soil water balance, erosion, nutrient cycling, and plant growth, and simulates the transport of water, sediment, and nutrients from each HRU to the watershed outlet.

SWAT requires input data such as weather data, soil properties, land use, and management practices, which are usually obtained from various sources, including remote sensing and ground-based measurements[5]. The model outputs various hydrological and water quality variables such as streamflow, sediment yield, nutrient loads, and crop yield, which can be used to assess the impact of different land management scenarios and climate change on water resources and environmental quality. SWAT model uses water balance equation for simulation. Flowchart demonstrates the methodology of futuristic streamflow forecasting, flood plain mapping and frequency analysis as demonstrated by Figure 1-9.

[5] Haleem, K., Khan, A.U., Ahmad, S., Khan, M., Khan, F.A., Khan, W., Khan, J., 2022. Hydrological impacts of climate and land-use change on flow regime variations in upper Indus basin. Journal of Water and Climate Change 13, 758-770.

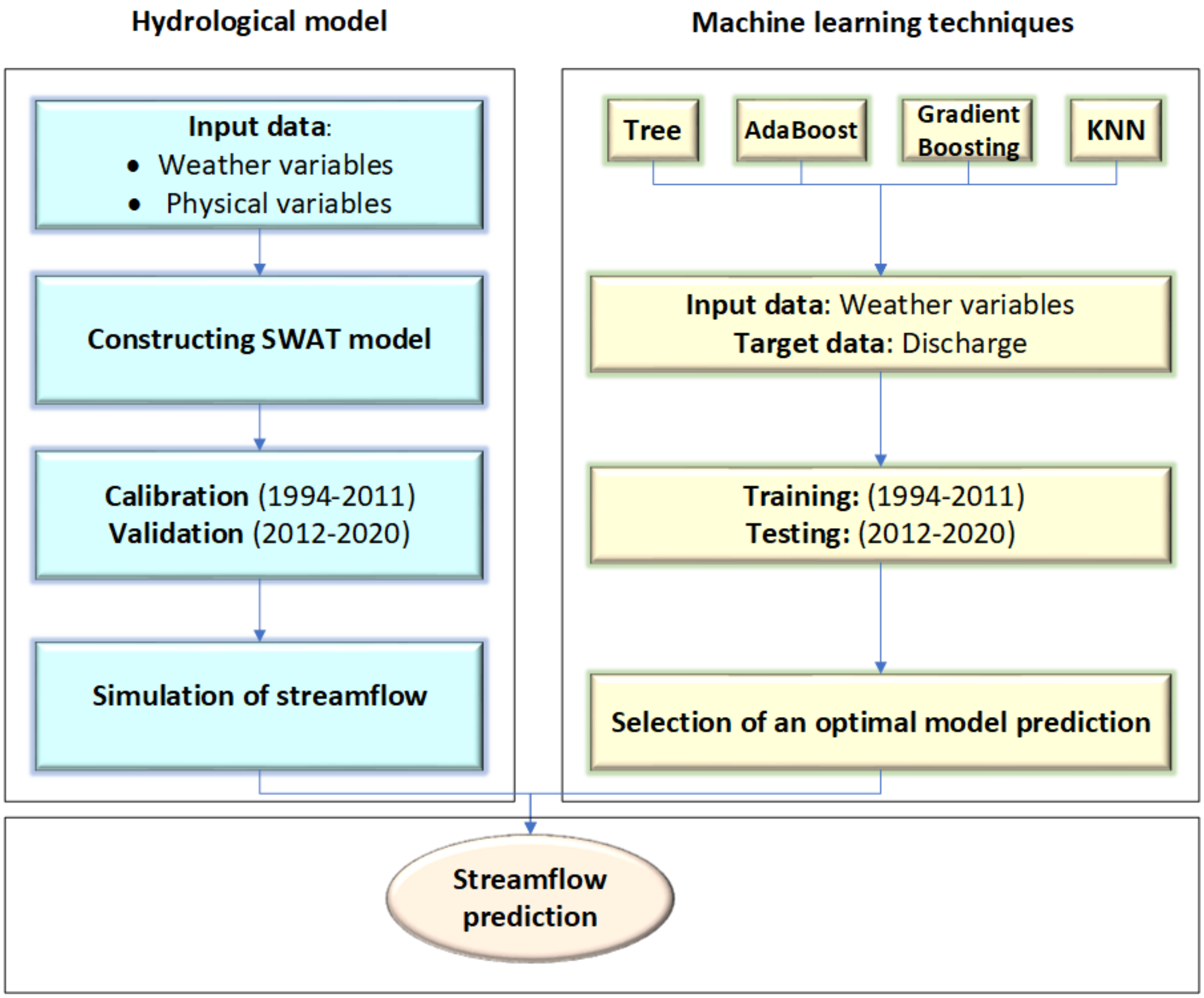

Figure 1-9: Flowchart demonstrating methodology of the current study

1.3.2 SWAT Model Calibration and Validation

SWAT Calibration and Uncertainty Program (SWAT-CUP) is used for the calibration of SWAT models. The program performs calibration, validation, sensitivity analysis (one-at-a-time), and uncertainty analysis. In addition, the program links Sequential Uncertainty Fitting program algorithm (SUFI2), Generalized likelihood Uncertainty Estimation (GLUE), Parameter Solution (ParaSol), Markov Chain Monte Carlo (MCMC), and Particle Swarm Optimization (PSO) algorithms to SWAT[6]. For better results, the SWAT-CUP model uses 2/3 of the data for calibration and 1/3 of the data for validation.

[6] Shang, X., Jiang, X., Jia, R., Wei, C., 2019. Land use and climate change effects on surface runoff variations in the upper Heihe River basin. Water 11, 344

SWAT-CUP was calibrated using monthly data from 1993-2011, and validated from 2012-2020. The model accuracy was assessed through several statistical indicators i.e., NSE, RRMSE, and percent bias (PBIAS). The model efficiency will be tested in the validated period through several statistical indicators.

1.4 Flood Frequency Analysis

Flood frequency analysis is a statistical method used to estimate the probability of occurrence of floods of different magnitudes in a given river or stream. The analysis is based on the historical flood data, which is used to estimate the frequency and magnitude of future floods. Flood frequency analysis is an important tool for designing hydraulic structures, such as bridges, culverts and dams, and for developing flood management strategies.

The basic steps in flood frequency analysis are as follows:

- Collect historical flood data: The first step in flood frequency analysis is to collect historical flood data, which includes the flood peak discharge and the corresponding recurrence interval or return period.
- Estimate the probability distribution of flood peaks: The next step is to estimate the probability distribution of flood peaks using statistical methods, such as the Gumbel distribution or the Log-Pearson Type III distribution etc.
- Estimate the parameters of the probability distribution: Once the probability distribution is selected, the parameters of the distribution are estimated using the historical flood data.
- Calculate the design flood: The design flood is the flood magnitude that has a certain probability of occurrence, usually expressed as the return period.

2 Climate Change Projections for the Project Locations

2.1 Global Climate Models

GCMs, also known as general circulation models, are complex computer programs that simulate the Earth's climate system. They use mathematical equations to model the interactions between the atmosphere, oceans, land surface, and ice, and to predict how the climate will change in response to different scenarios.

The models are based on fundamental principles of physics, such as the conservation of energy and mass, and include a range of physical, chemical, and biological processes that affect the Earth's climate, such as the absorption and reflection of solar radiation, the movement of heat and moisture in the atmosphere and oceans, and the growth and decay of vegetation and ice.

The models are typically run on supercomputers and divided into a three-dimensional grid, with each cell representing a small portion of the Earth's surface as obvious from Figure 2-1. The equations are solved for each cell and for each time step, typically ranging from hours to years. GCMs are used to make projections of future climate change under different greenhouse gas emission scenarios. They are also used to study the Earth's past climate and to understand the natural variability of the climate system.

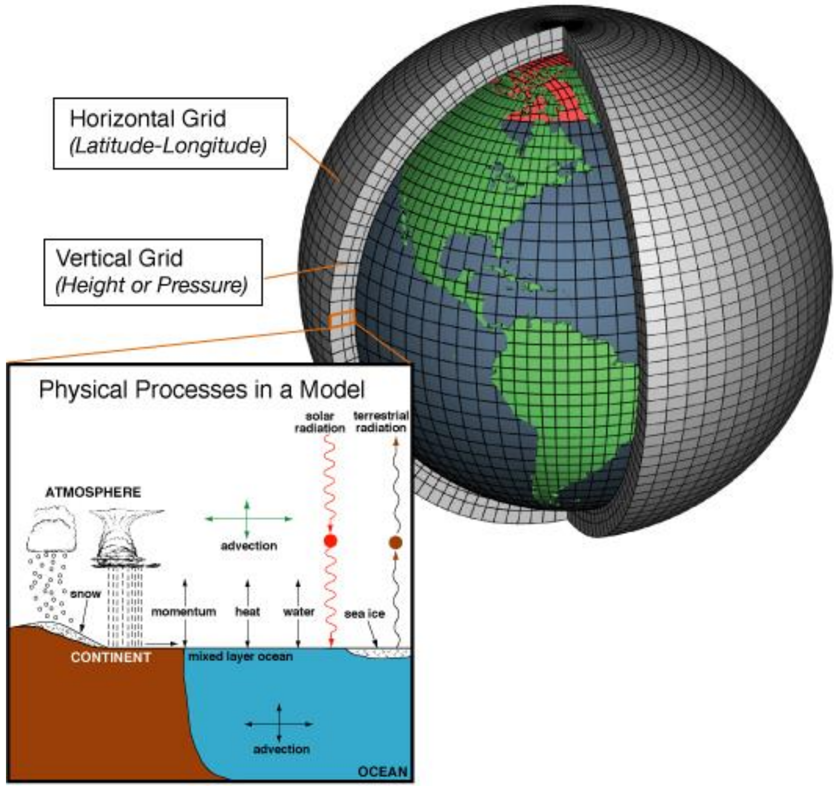

Figure 2-1: Conceptual representation of GCMs[7]

CMIP6 (Coupled Model Intercomparison Project Phase 6) is the most recent version of the international project that aims to improve our understanding of the Earth's climate system by comparing the output from different GCMs under standardized scenarios. One of the key features of CMIP6 is the inclusion of more detailed representations of Earth system processes, such as the carbon cycle, biogeochemical cycles, and atmospheric chemistry, in the climate models. This is intended to improve the models' ability to simulate the Earth's climate system and to make more accurate projections of future climate change.

SSPs are a set of socio-economic scenarios that describe different possible futures in terms of how societies might develop over the 21st century. They consider a range of factors such as population growth, economic development, technological change, and governance structures, and describe how these factors might interact to shape the future.

[7] NOAA 2008

The SSPs are used as input to climate models to explore how different socio-economic trajectories might lead to different climate outcomes.

CMIP6 is based on five SSPs scenarios. SSP1 (Sustainability) has low challenges to both mitigation and adaptation. In this scenario, policies focus on human well-being, clean energy technologies, and the preservation of the natural environment. In contrast, SSP3 (Regional Rivalry) is characterized by high challenges to both mitigation and adaptation. In this scenario, nationalism drives policy and focus is placed on regional and local issues rather than global issues. SSP4 (Inequality) is defined by high challenges to adaptation and low challenges to mitigation, SSP5 (Fossil-fueled Development) is characterized by high challenges to mitigation and low challenges to adaptation, and SSP2 (Middle of the Road) represents moderate challenges to both mitigation and adaptation. The SSPs five domains and CMIP6 scenarios based on anthropogenic radiative forcing are provided in Figure 2-2 and Figure 2-3.

Figure 2-2: The SSPs having five domains based on challenges for mitigation and adaptation to climate change[8]

[8] O'Neill et al. (2014)

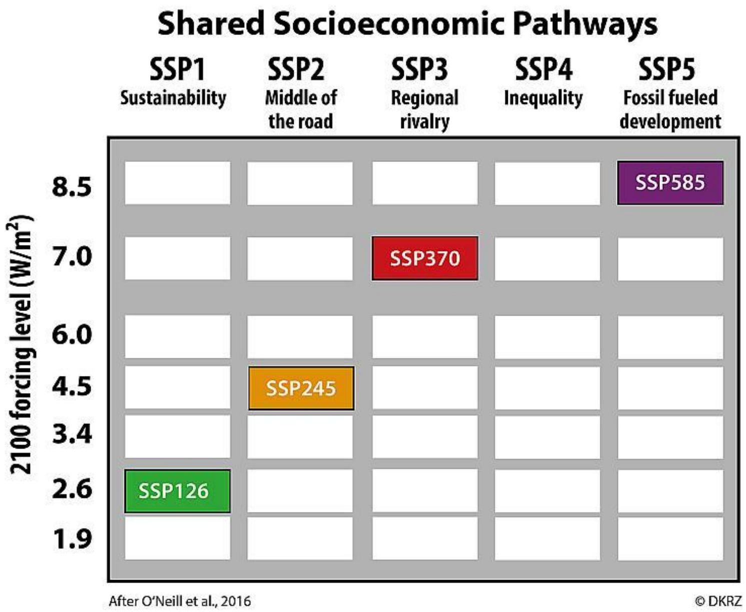

Figure 2-3: CMIP6 scenarios based on anthropogenic radiative forcing[8]

The present study is based on two CMIP6 scenarios i.e., SSP245 and SSP585. The selected 10 GCMs MME data was compared with 31 ensemble GCMs data which is adopted from World Bank's climate knowledge portal. Both precipitation and temperature variations were projected for the period of 2021-2100. The projections of the aforementioned parameters are explained in the following sections.

2.2 Projected Climatic Variables for the Region

Using the World Bank Climate Change Knowledge Portal Data, the precipitation anomly ranges between -3 to 7mm and -4 to 12mm under SSP245 and SSP585 scenerios respectively as obvious from Figure 2-4 and Figure 2-5. Similarly, the temperature anomly ranges between -2 to 4 ^{0}C and -2 to 7 ^{0}C under SSP245 and SSP585 scenerios respectively as obvious from Figure 2-7 and Figure 2-8. This shows that the projected monthly precipitation and temperature is expected to increase in the coming decades as compared to reference period (1995-2014) under SSP245 and SSP585 scenerios.

The findings predicted a hot and wet climate over the next three decades. Adaptation policies should be developed based on the findings to mitigate the potential impacts of climate change.

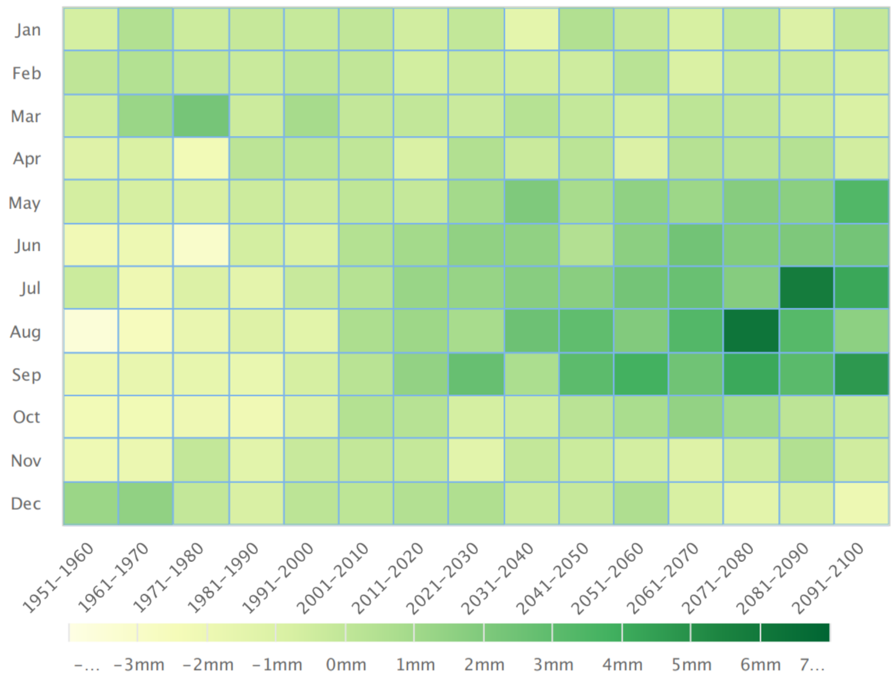

Figure 2-4: Projected monthly precipitation decadal variation compared to base period (1985-2014) using ensemble of 31 GCMs for SSP245 scenario. (Source: based on World Bank Knowledge Portal)

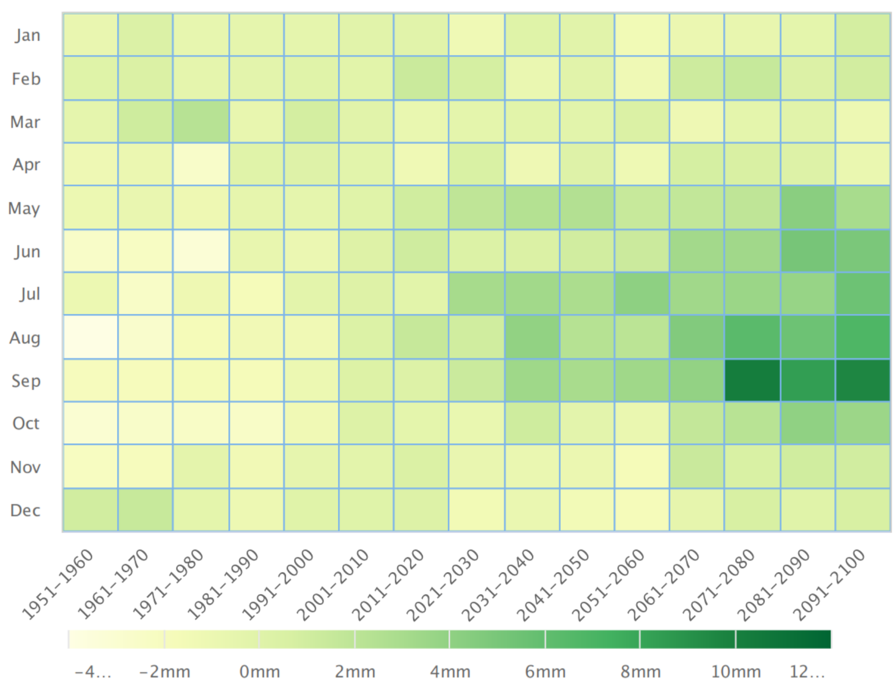

Figure 2-5: Projected monthly precipitation decadal variation compared to base period (1985-2014) using ensemble of 31 GCMs for SSP585 scenario. (Source: based on World Bank Knowledge Portal)

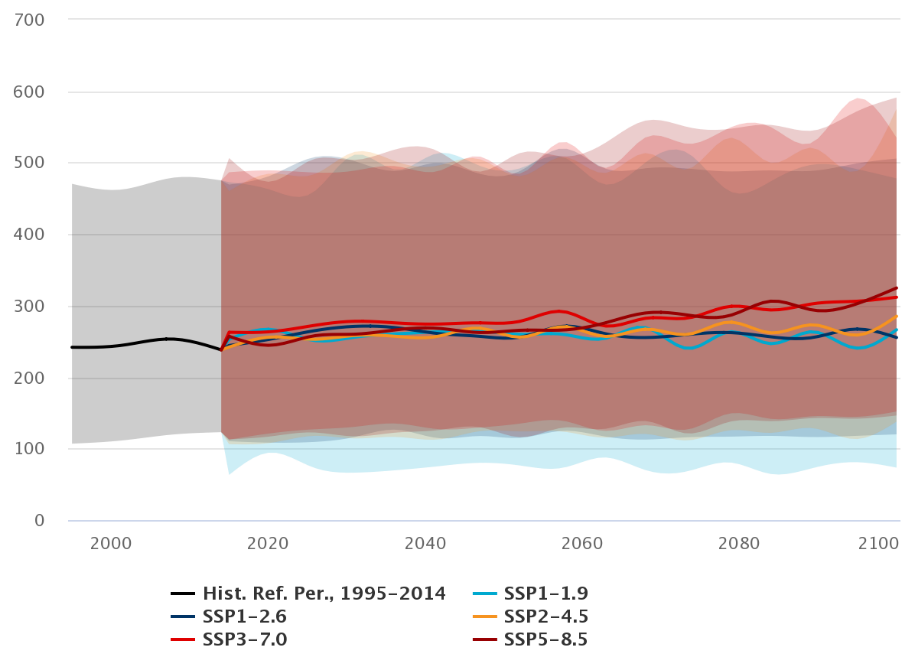

Figure 2-6: Projected precipitation variation during (2015-2100) compared to base period (1995-2014) using SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP-3-7.0, SSP5-8.5 scenario, MME. (Source: based on World Bank Knowledge Portal)

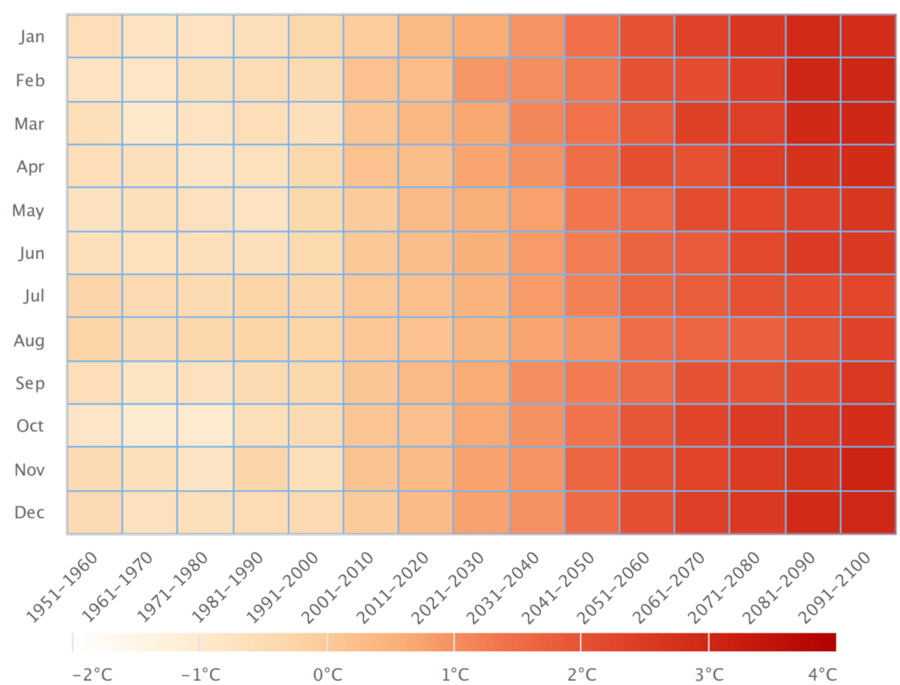

Figure 2-7: Projected mean monthly decadal temperature variation compared to base period (1985-2014) using ensemble of 31 GCMs for SSP245 scenario. (Source: based on World Bank Knowledge Portal)

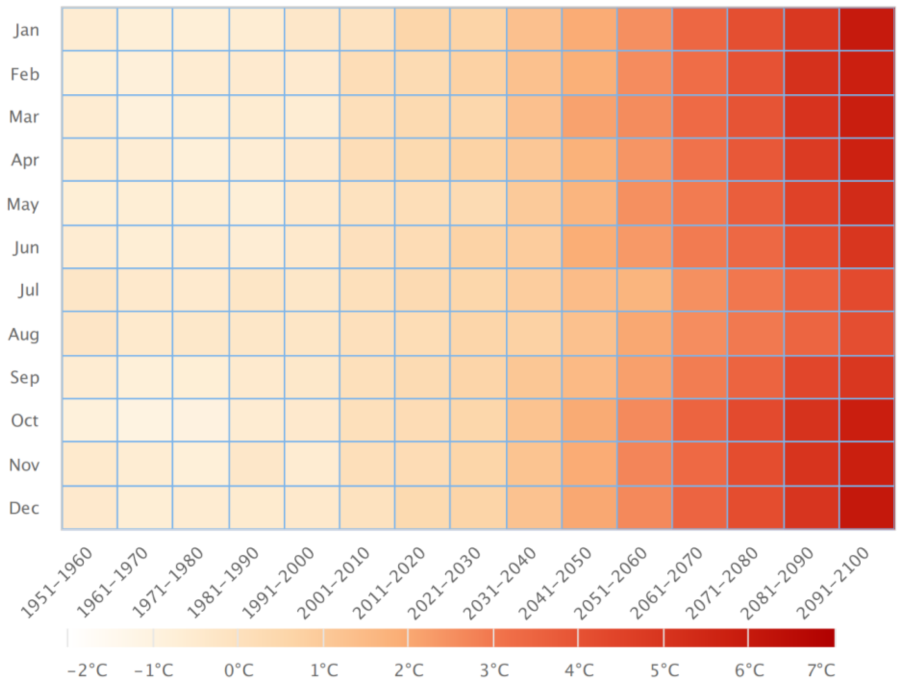

Figure 2-8: Projected mean monthly decadal temperature variation compared to base period (1985-2014) using ensemble of 31 GCMs for SSP585 scenario. (Source: based on World Bank Knowledge Portal)

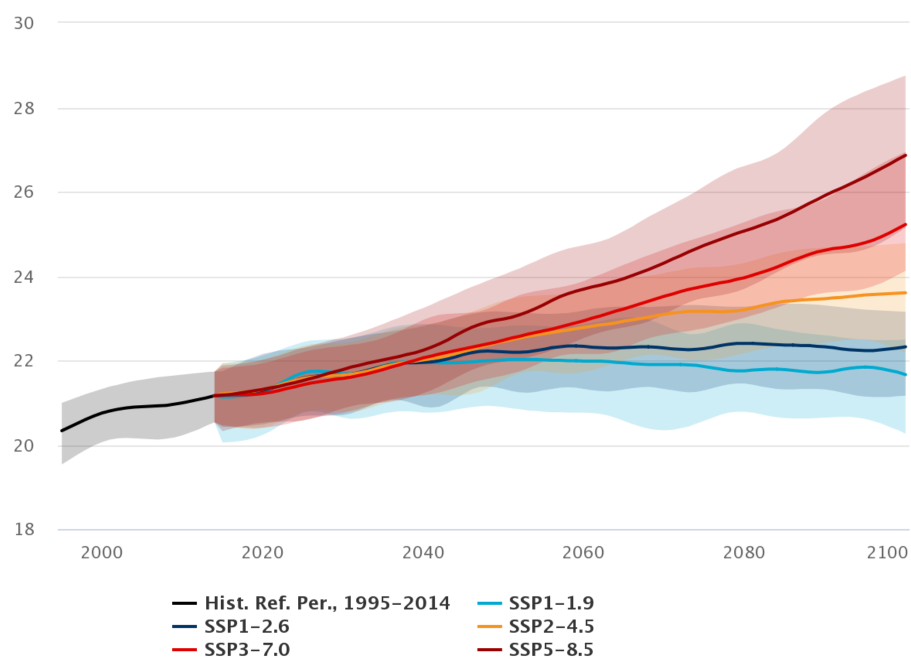

Figure 2-9: Projected mean temperature variation during (2015-2100) compared to base period (1995-2014) using SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP-3-7.0, SSP5-8.5 scenario, MME. (Source: based on World Bank Knowledge Portal)

2.3 Projected Climatic Variable for the Study Area

Air temperature and precipitation are the main determinants of weather systems. Both parameters have a significant impact on the water cycle. Examination of their behavior is important for understanding the climate variability. Both variables vary spatio-temporaly at local, regional and global scales. For better prediction of climatic conditions, level of variability of these two weather elements must be examined and understood.

The precipitation anomly ranges between -1.4 to 3.78mm and -1.14 to 6.48 mm for Swat and Lower Dir region under SSP245 and SSP585 scenerios respectively as obvious from Figure 2-12 and Figure 2-16. The precipitation anomly ranges between -0.82 to 1.44 mm and –0.6 to 2.11 mm for Charsadda and Nowshera under SSP245 and SSP585 scenerios respectively as obvious from Figure 2-13 and Figure 2-17.

The temperature anomly ranges between -1.62 to 3.94 ^{0}C and -1.65 to 7.65 ^{0}C for Swat and Lower Dir region under SSP245 and SSP585 scenerios respectively as obvious from Figure 2-10 and Figure 2-14.. The temperature anomly ranges between -1.16 to 4.06 ^{0}C and -1.16 to 7.78 ^{0}C for Charsadda and Nowshera region under SSP245 and SSP585 scenerios respectively as obvious from Figure 2-11 and Figure 2-15. This shows that the projected monthly precipitation and temperature is expected to increase in the coming decades as compared to reference period (1993-2022) under SSP245 and SSP585 scenerios.

The increase in air temperature and precipitation depicts a hot and wet climate over the next three decades in the study area. These findings are parallel with the Climate Change Knowledge Portal futuristic simulations.

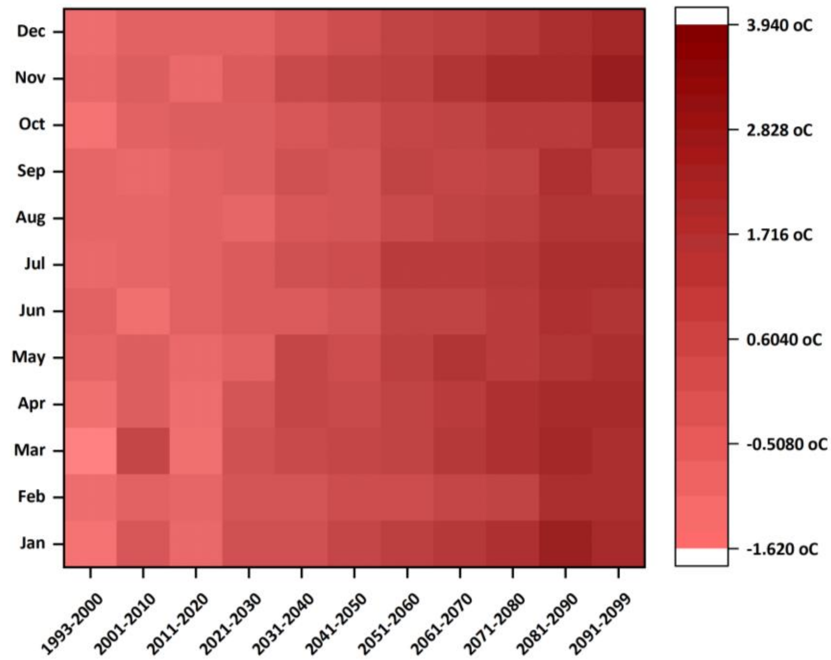

Figure 2-10: Temperature decadal variation for Swat and Lower Dir selected MMEs out of 10 GCMs for SSP245 scenario based on linear scaling bias correction technique.

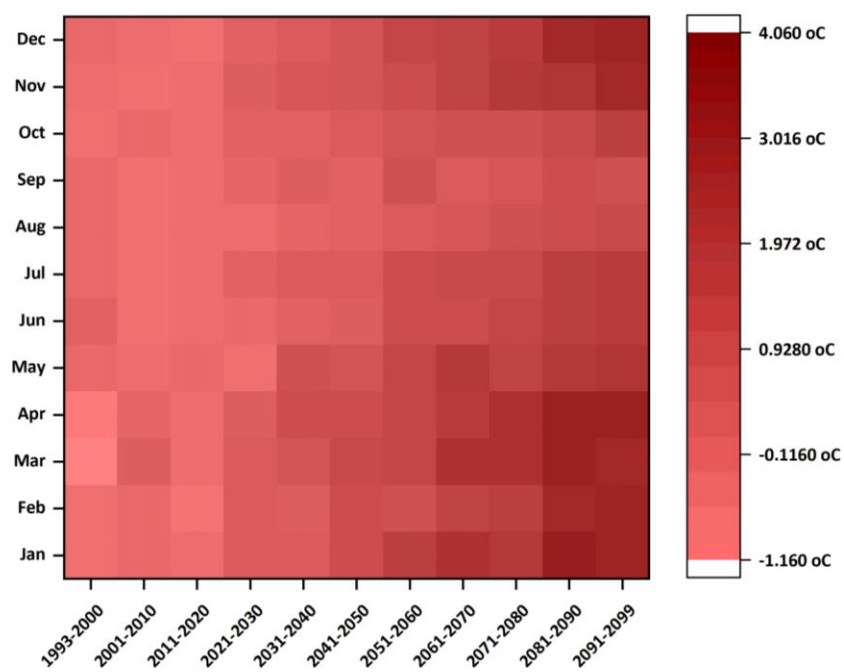

Figure 2-11: Temperature decadal variation for Charsadda and Nowshera using selected MMEs out of 10 GCMs for SSP245 scenario based on linear scaling bias correction technique.

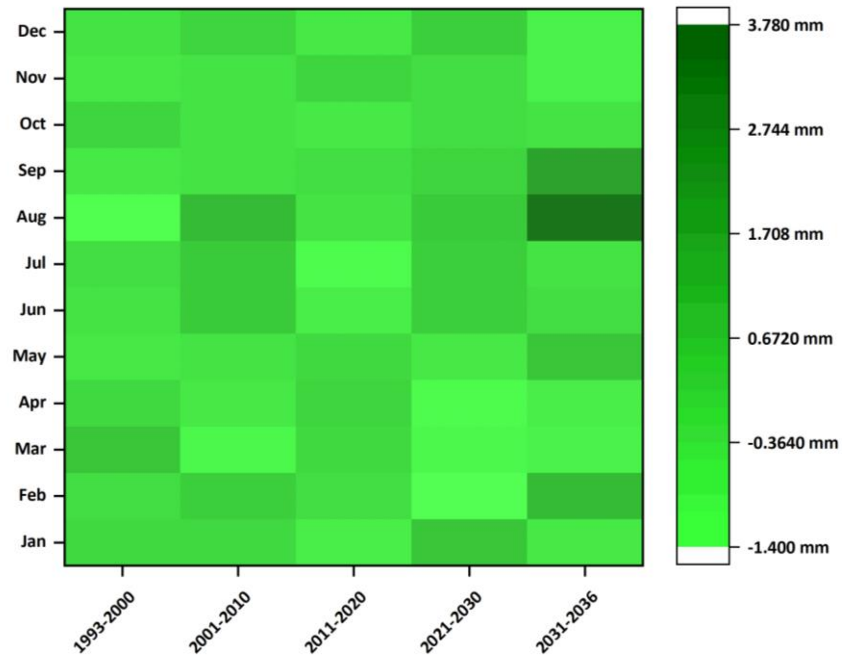

Figure 2-12: Precipitation decadal variation of Swat and Lower Dir using selected MMEs out of 10 GCMs for SSP245 scenario based on linear scaling bias correction technique.

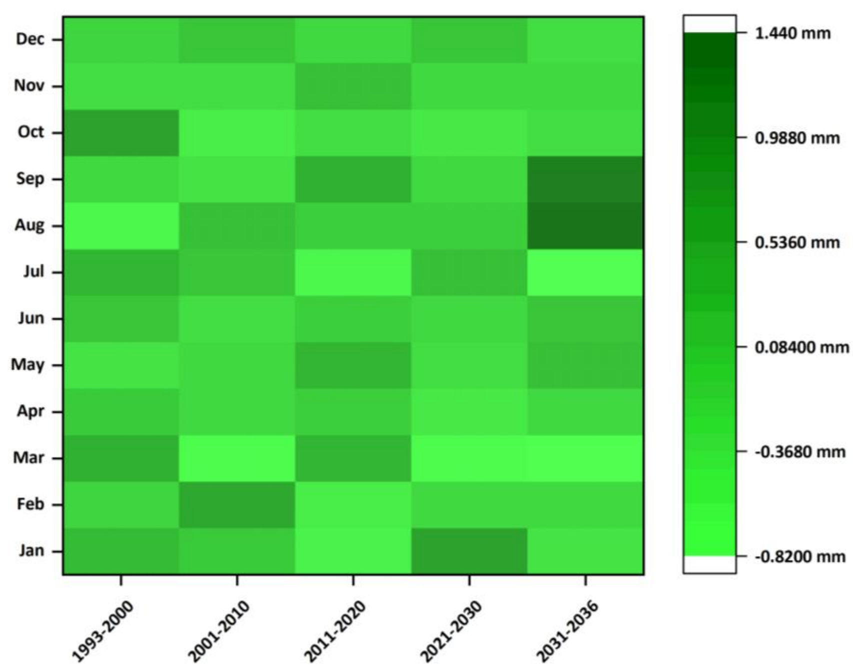

Figure 2-13: Precipitation decadal variation of Charsadda and Nowshera using selected MMEs out of 10 GCMs for SSP245 scenario based on linear scaling bias correction technique.

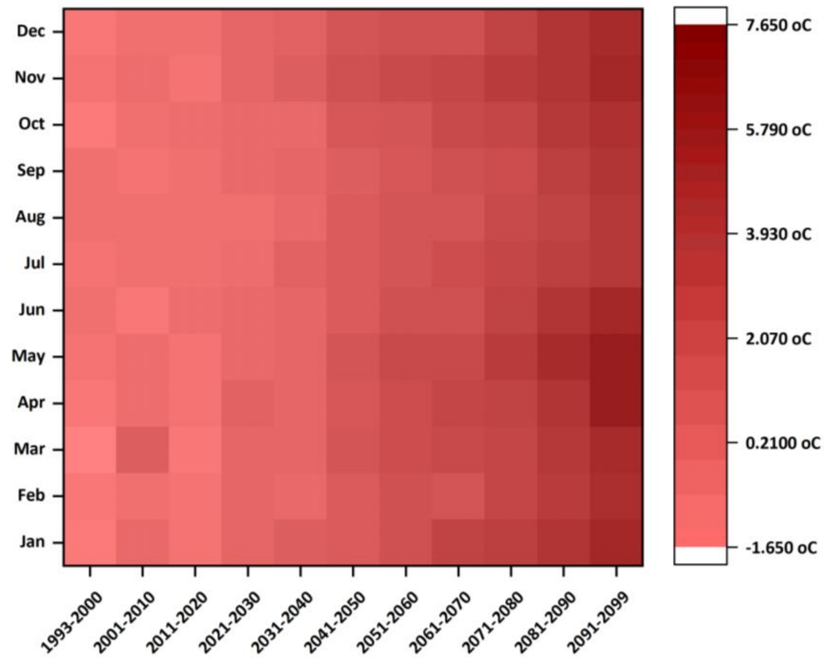

Figure 2-14: Temperature decadal variation of Swat and Lower Dir using selected MMEs out of 10 GCMs for SSP585 scenario based on linear scaling bias correction technique.

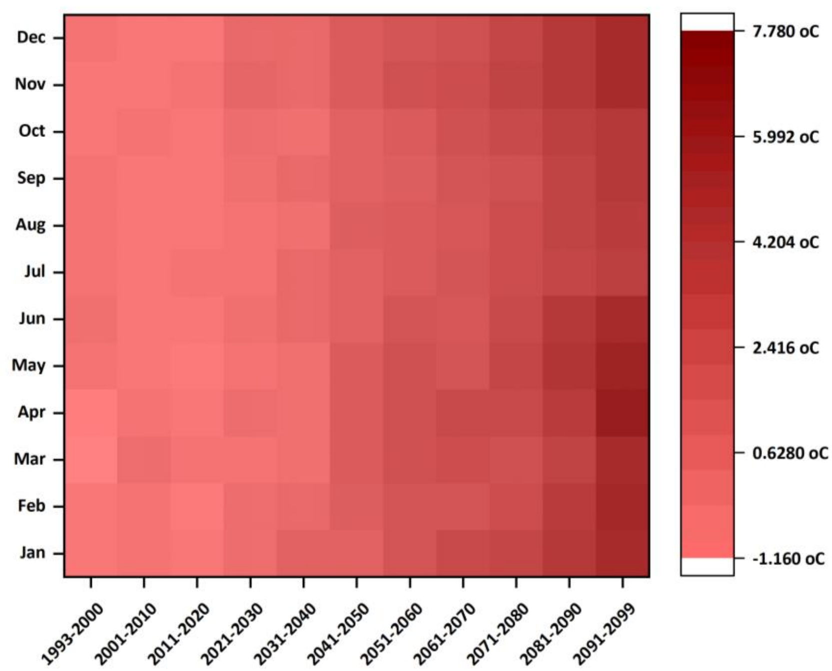

Figure 2-15: Temperature decadal variation of Charsadda and Nowshera using selected MMEs out of 10 GCMs for SSP585 scenario based on linear scaling bias correction technique.

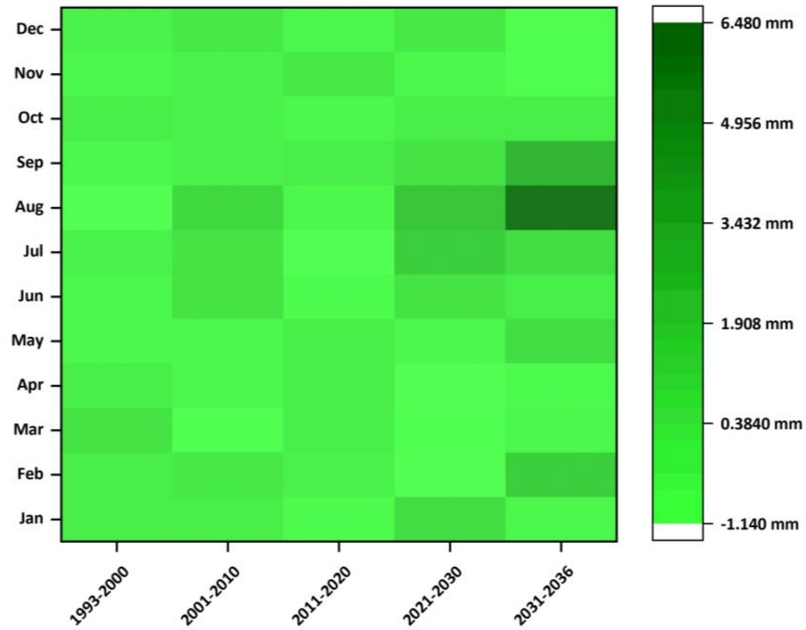

Figure 2-16: Precipitation decadal variation of Swat and Lower Dir using selected MMEs out of 10 GCMs for SSP585 scenario based on linear scaling bias correction technique.

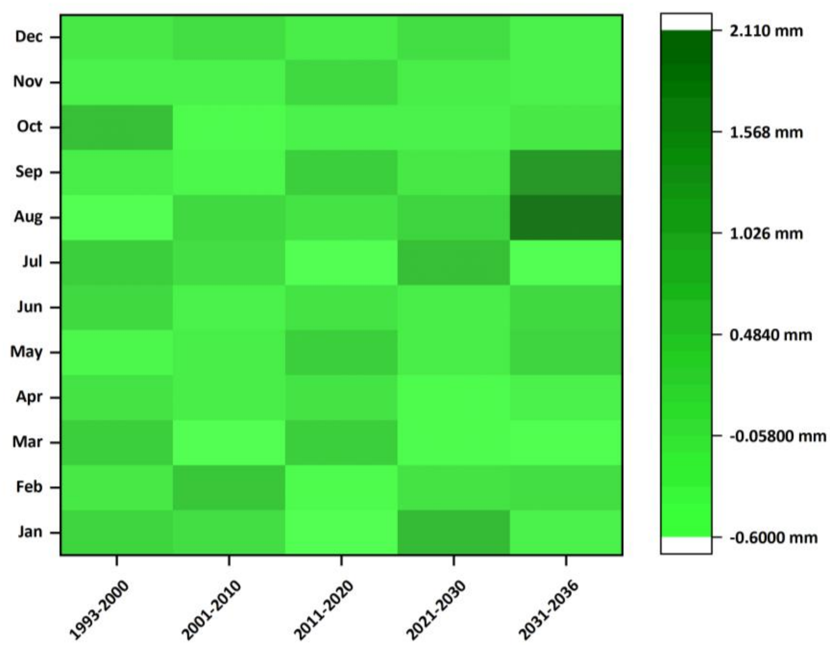

Figure 2-17: Precipitation decadal variation of Charsadda and Nowshera using selected MMEs out of 10 GCMs for SSP585 scenario based on linear scaling bias correction technique.

2.4 Bias Correction of GCM

Linear scaling (additive and multiplicative) and delta change correction technique were used for the present study using CMhyd tool. The model accuracy was assessed through several statistical indicators i.e. NSE, R^2, and RMSE. The results are listed in Table 2-1 and Table 2-2. The linear scaling appraoch is superior in predicitng temperature minimum and maximium incomparison to precipitation as obvious from the statistical performance indicators listed in Table 2-1. To overcome the aforementioned problem Delta Change Correction technique was applied. Delta Change Correction technique produced statistically significant results for precipitation incomparisn to linear scaling approach as obvious from Table 2-2.

Table 2-1: Bias correction of GCMs output using Linear Scaling technique

Station	Variable	SSP	R^2	RMSE	NSE
Saidu Sharif (Linear Scaling Method)	Precipitation	245	0.00729	10.01	-0.23
	Tmax		0.72	4.11	0.71
	Tmin		0.84	3.32	0.83
	Precipitation	585	0.001	11.61	-0.43
	Tmax		0.75	3.86	0.73
	Tmin		0.85	2.84	0.83
Peshawar (Linear Scaling Method)	Precipitation	245	0.001	6.05	-0.13
	Tmax		0.69	11.55	0.65
	Tmin		0.83	8.17	0.77
	Precipitation	585	0.001	6.13	-0.16
	Tmax		0.68	11.85	0.63
	Tmin		0.79	12.17	0.73

Table 2-2: Bias correction of GCMs output using Delta Change Correction technique

Station	Meteorological parameter	SSP	R^2	RMSE	NSE
Saidu Sharif	Precipitation	245	0.98	0.95	0.97
	Precipitation	585	0.95	0.91	0.93
Peshawar	Precipitation	245	0.97	0.63	0.97
	Precipitation	585	0.92	0.96	0.86

2.5 Rating Matric and Taylor Skill Score

MMEs are used for improving the performance of GCM simulations. In this project TSS and RM are used to bring in front the most suitable combination of GCMs for the computation of MMEs. The details are demonstrated by Figures Figure 2-18 to Figure 2-21.

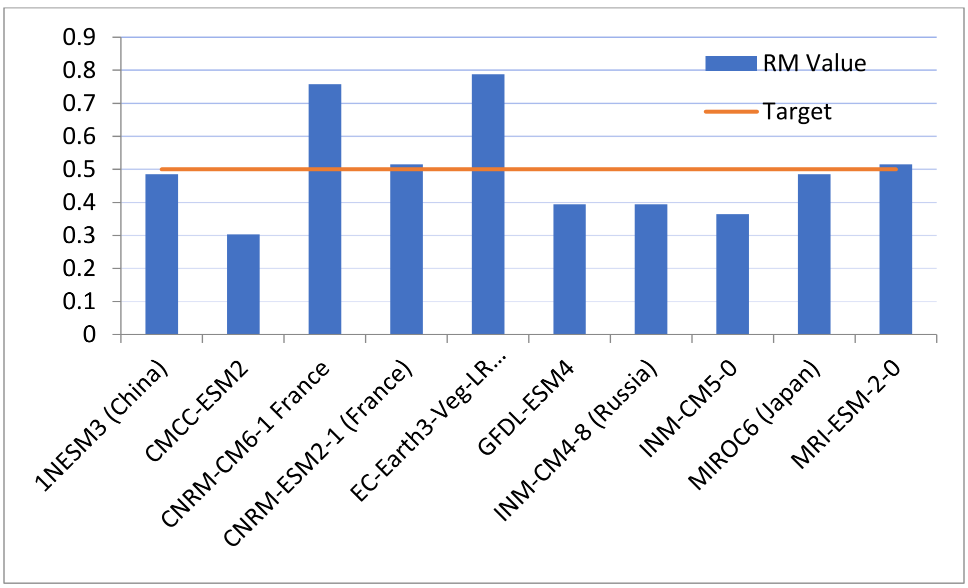

Figure 2-18: TSS and RM of Saidu Sharif for MME computation using 10 GCMs for SSP245 scenario based on linear scaling bias correction technique.

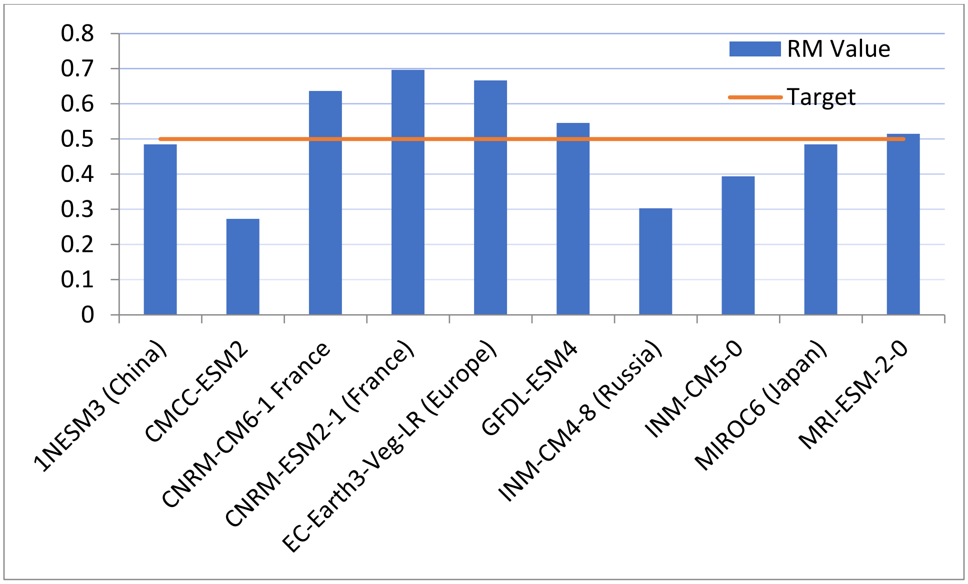

Figure 2-19: TSS and RM of Peshawar for MME computation using 10 GCMs for SSP245 scenario based on linear scaling bias correction technique.

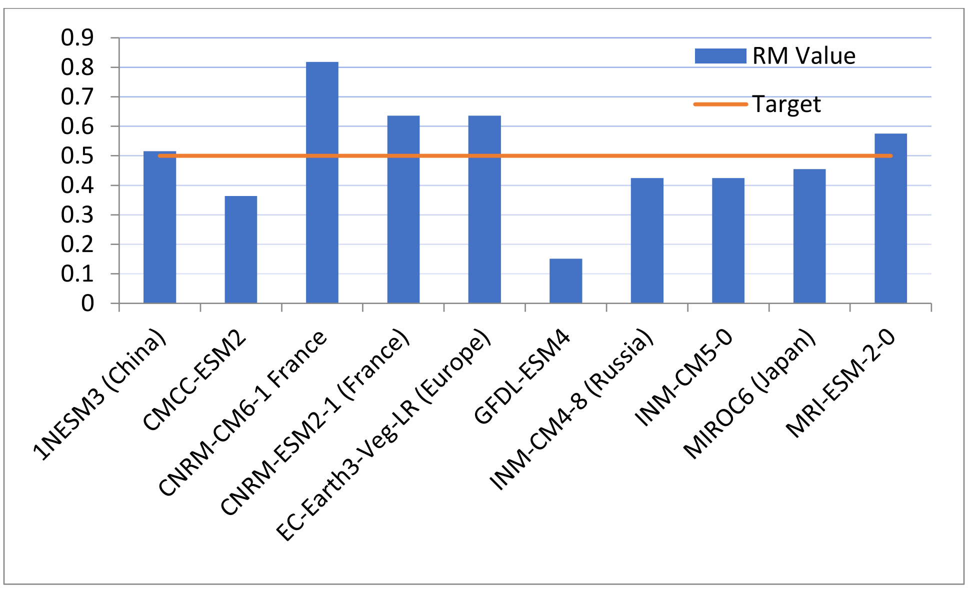

Figure 2-20: TSS and RM of Saidu Sharif for MME computation using 10 GCMs for SSP585 scenario based on linear scaling bias correction technique.

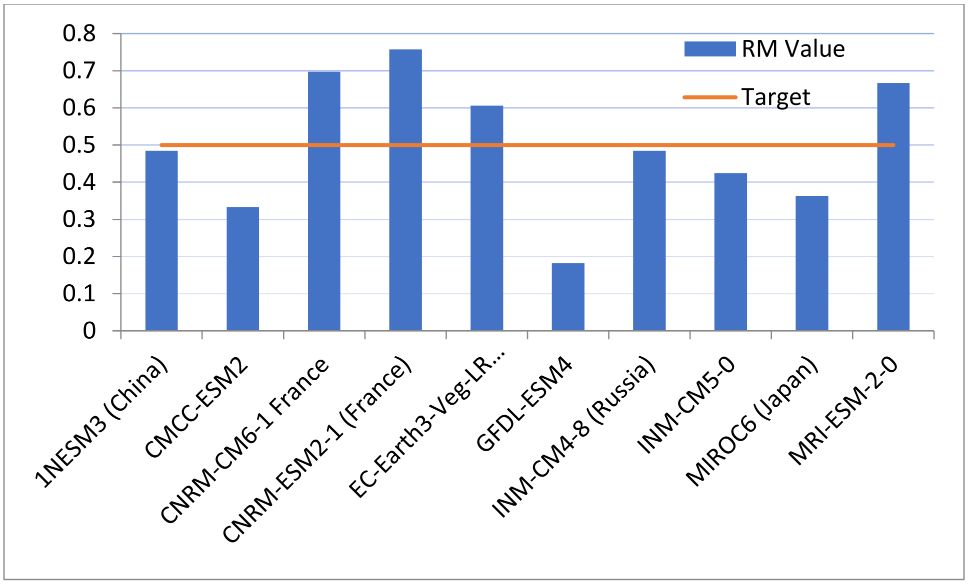

Figure 2-21: TSS and RM of Peshawar for MME computation using 10 GCMs for SSP585 scenario based on linear scaling bias correction technique.

2.6 Temporal Variation of Precipitation and Temperature

Rainfall and temperature are two important climatic variables that exhibit temporal variation. The patterns of variation can vary depending on the location and other environmental factors. Generally, rainfall and temperature exhibit both short-term and long-term variations. Variations in rainfall and temperature are influenced by a variety of factors and can have significant impacts on ecosystems and human populations. Understanding these variations is essential for predicting future climate patterns and developing effective strategies for adapting to changing climatic conditions. Temporal variation of temperature and precipitation at Swat and Lower Dir and Charsadda and Nowshera using selected MME out of 10 GCMs for SSP245 and SSP585 scenarios are demonstrated by Figure 2-22 to Figure 2-31.

2.6.1 Swat and Lower Dir Region

Temporal variation of temperature and precipitation for Swat and Lower Dir region using selected MME out of 10 GCMs for SSP245 and SSP585 scenarios are demonstrated by Figure 2-22 to Figure 2-26.

For the region, the rise in maximum temperature is projected to be 2.77 °C and 5.77 °C under SSP245 and SSP585 scenarios respectively, by the end of the century. Similarly, an increase in the minimum temperature is projected to be 2.53 °C and 5.70 °C under SSP245 and SSP585 scenario respectively, over the same period.

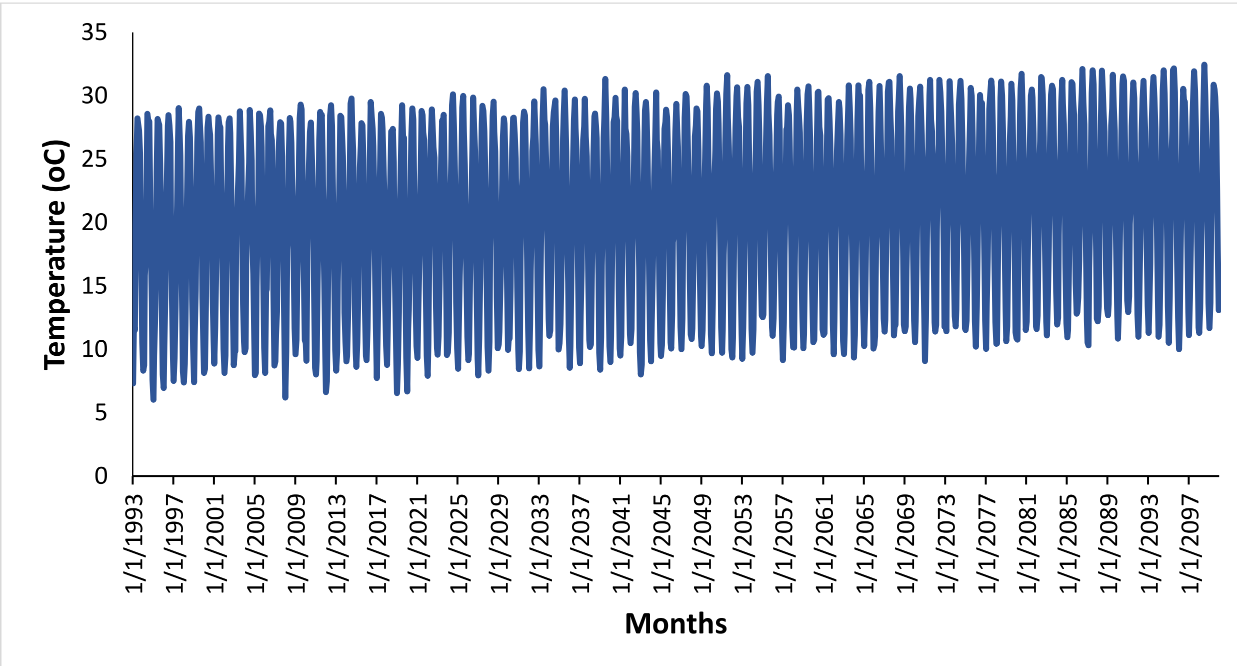

Figure 2-22: Temporal variation of temperature at Swat and Lower Dir using selected MMEs out of 10 GCMs for SSP245 scenario based on linear scaling bias correction technique.

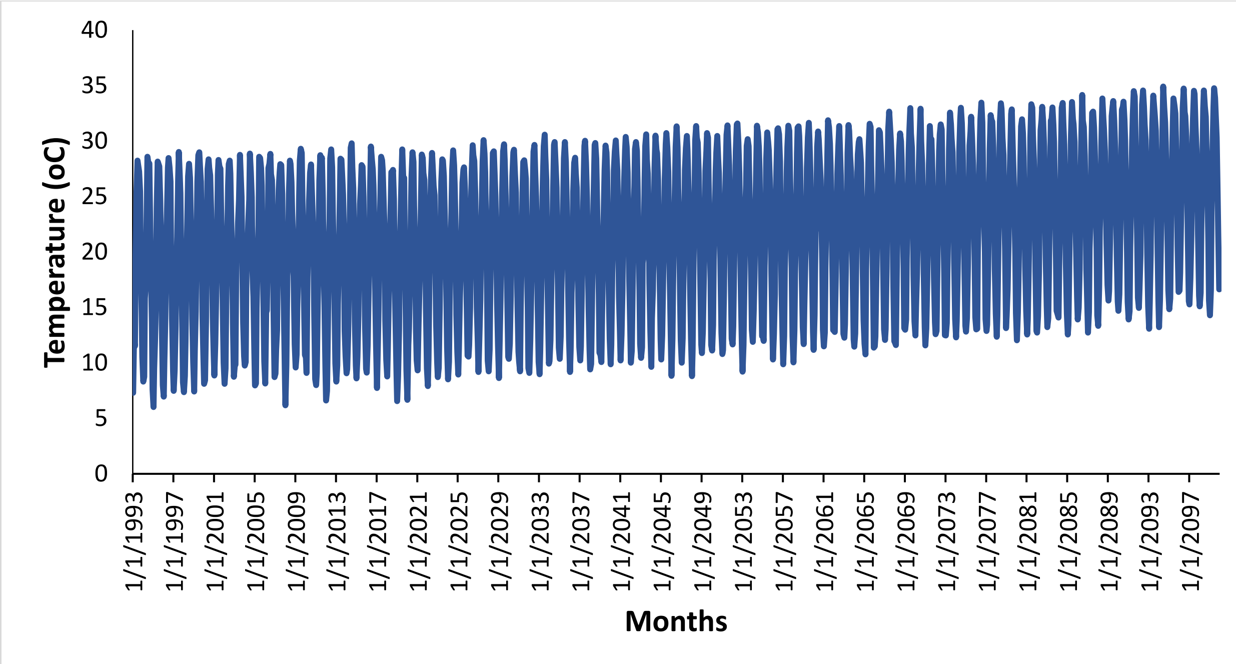

Figure 2-23: Temporal variation of temperature at Swat and Lower Dir using selected MMEs out of 10 GCMs for SSP585 scenario based on linear scaling bias correction technique.

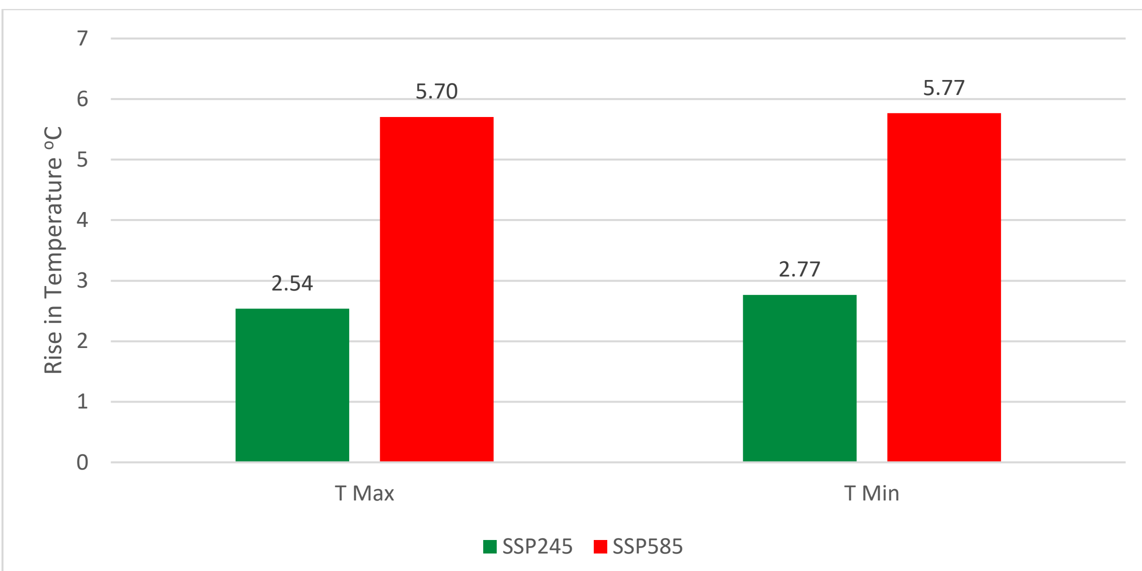

Figure 2-24: Rise in temperature in Swat and Lower Dir region under SSP245 and SSP585 scenarios till the end of the century

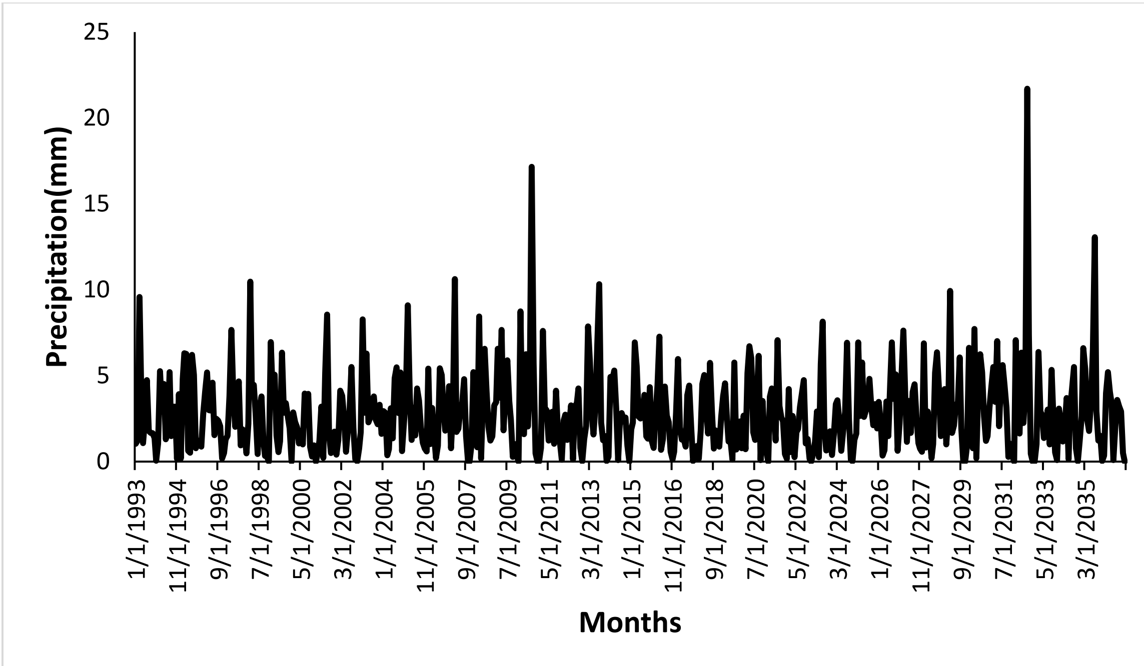

Figure 2-25: Temporal variation of precipitation at Swat and Lower Dir using selected MMEs out of 10 GCMs for SSP245 scenario based on linear scaling bias correction technique.

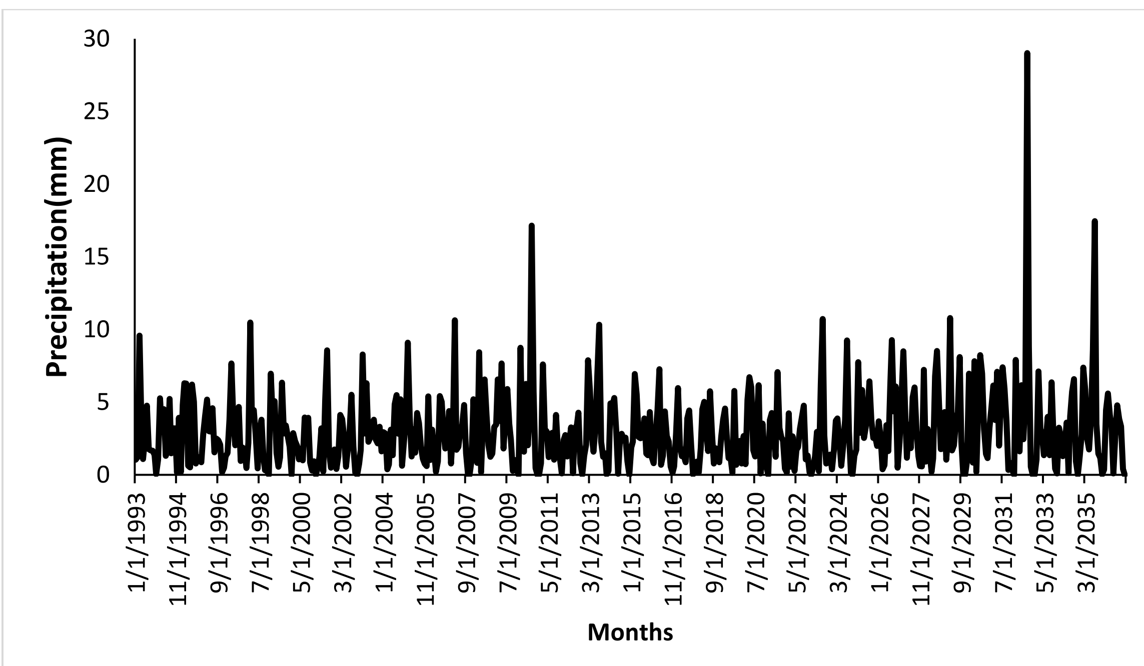

Figure 2-26: Temporal variation of precipitation at Swat and Lower Dir using selected MMEs out of 10 GCMs for SSP585 scenario based on linear scaling bias correction technique.

2.6.2 Charsadda and Nowshera Region

Temporal variation of temperature and precipitation for Charsadda and Nowshera region using selected MME out of 10 GCMs for SSP245 and SSP585 scenarios are demonstrated by Figure 2-27 to Figure 2-31.

For the region, the rise in maximum temperature is projected to be 2.81 ºC and 5.78 ºC under SSP245 and SSP585 scenarios respectively, by the end of the century. Similarly, an increase in the minimum temperature is projected to be 2.54 ºC and 5.62 ºC under SSP245 and SSP585 scenario respectively, over the same period.

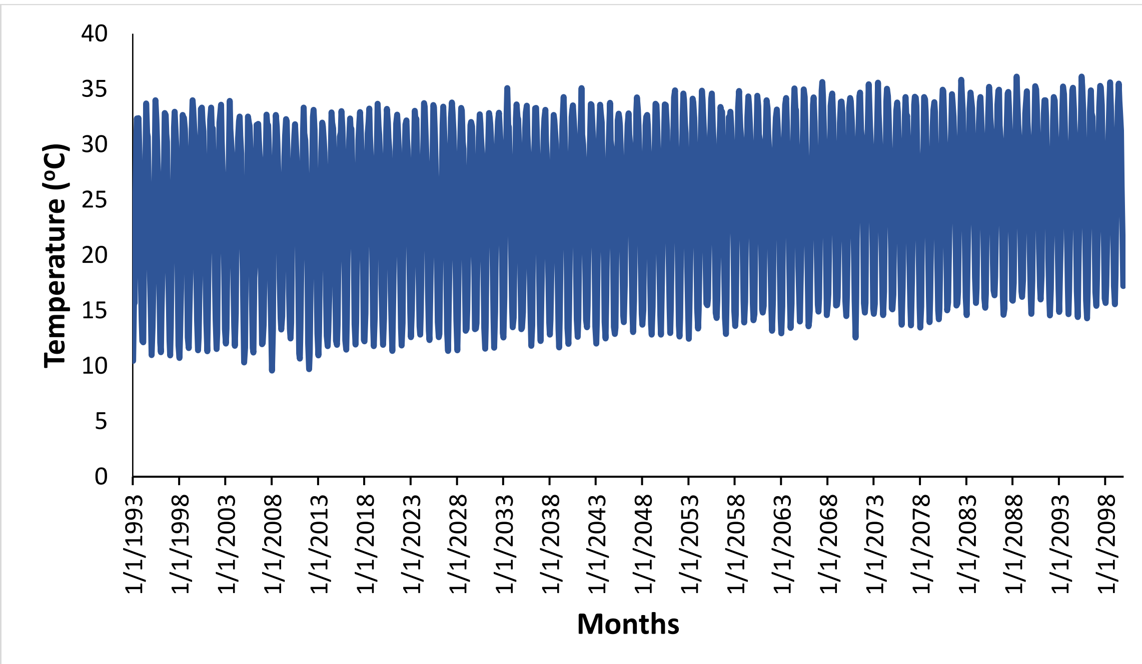

Figure 2-27: Temporal variation of temperature at Charsadda and Nowshera using selected MMEs out of 10 GCMs for SSP245 scenario based on linear scaling bias correction technique.

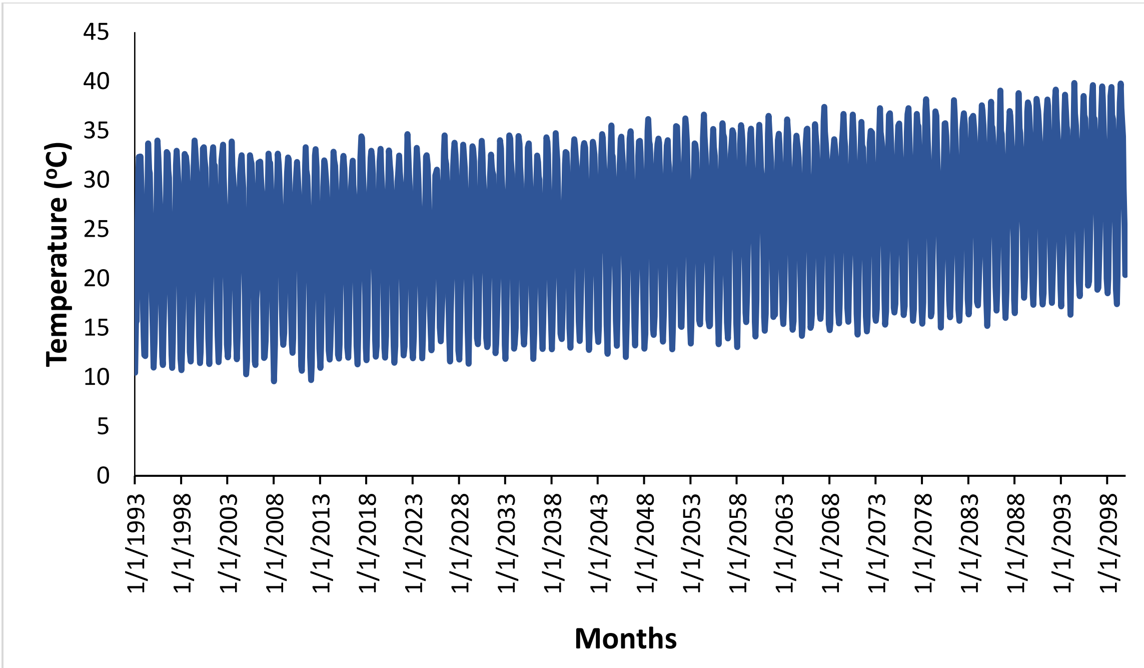

Figure 2-28: Temporal variation of temperature at Charsadda and Nowshera using selected MMEs out of 10 GCMs for SSP585 scenario based on linear scaling bias correction technique.

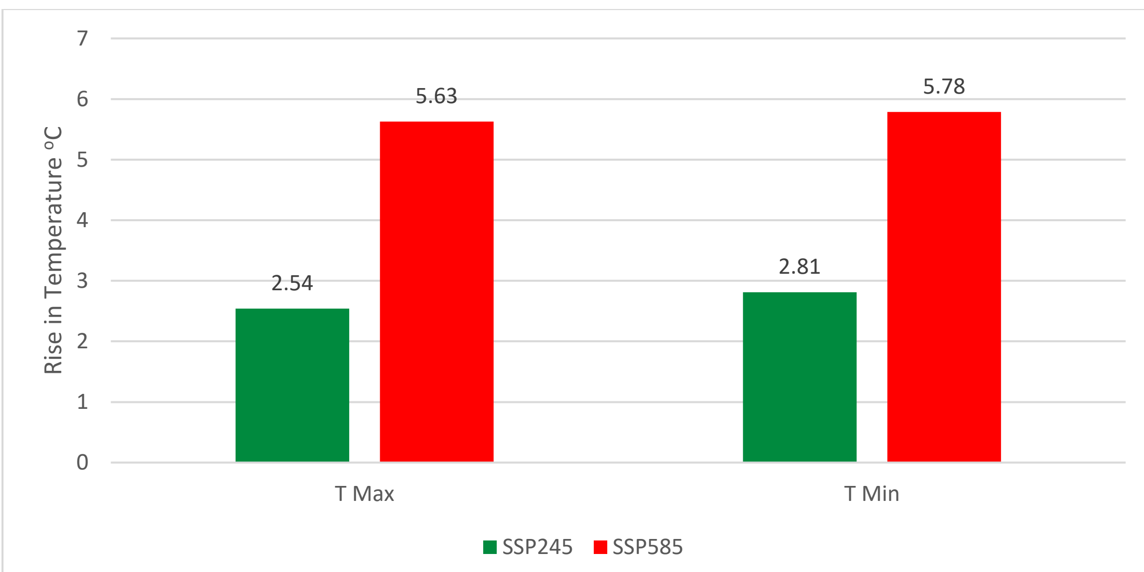

Figure 2-29: Rise in temperature in Charsadda and Nowshera region under SSP245 and SSP585 scenarios till the end of the century

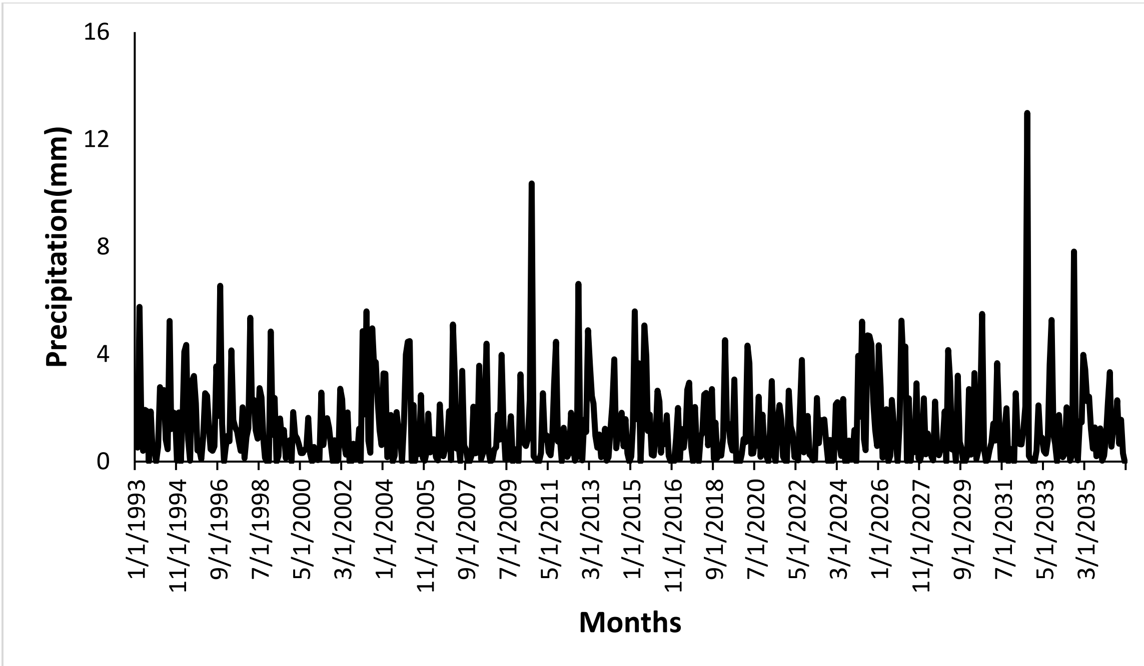

Figure 2-30: Temporal variation of precipitation at Charsadda and Nowshera using selected MMEs out of 10 GCMs for SSP245 scenario based on linear scaling bias correction technique.

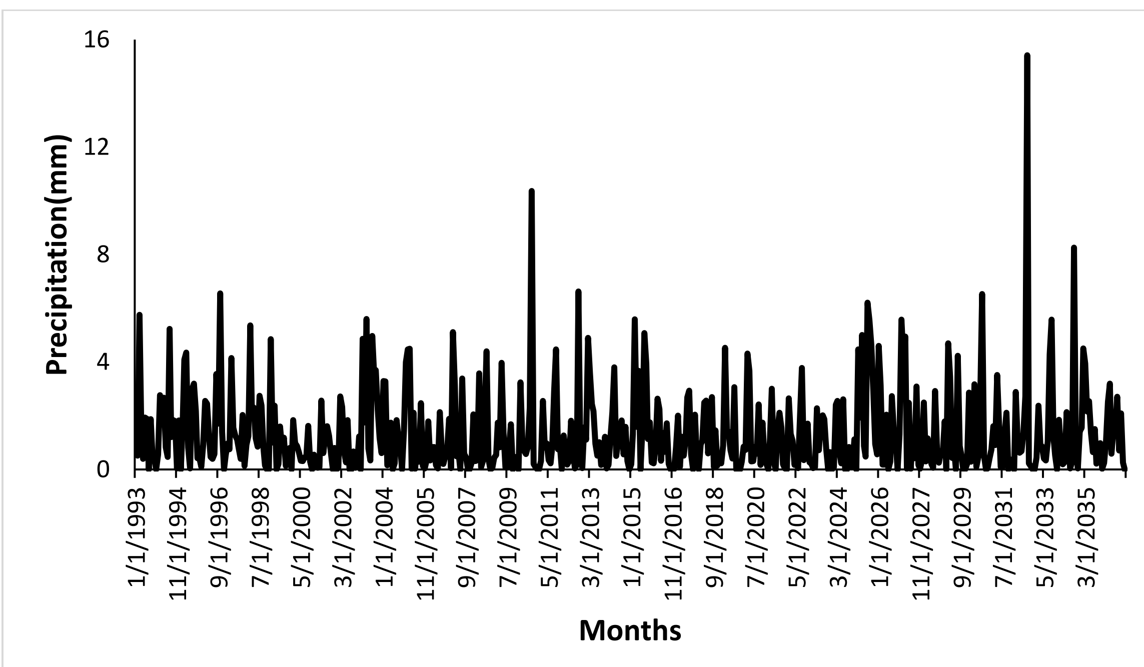

Figure 2-31: Temporal variation of precipitation at Charsadda and Nowshera using selected MMEs out of 10 GCMs for SSP585 scenario based on linear scaling bias correction technique.

3 Streamflow Computation and Flood Frequency Analysis

In this section of the report, detailed discussion on hydrological modelling is done. As discussed in the inception report, three different types of models are used in practice for hydrological modelling i.e., lumped models, semi-distributed models, and distributed model. In this study the first two approaches were used. In the initial phase of this study different lumped models based on Artificial Intelligence (Machine Learning Techniques) including AdaBoost, GradientBoosting, K-Nearest Neighbour and Decision Tree were used. In semi-distributed approach, SWAT model was used. This is to mention here that all the methods based on AI produced statistically insignificant results for the study basin. However, the semi-distributed model of SWAT produced statistically significant results. Hence, the results of SWAT hydrological model are used in this study. The details of the model and its calibration/validation are discussed in the following sections.

3.1 Swat Model Calibration and Validation

Calibration (1994–2011) and validation (2012–2020) of the observed flow data was carried out at Chakdara station located at Swat River. A warm-up period of 1 year (1993) was used to initialize the calibration process. The model calibration process was followed by sensitivity analysis to choose parameters that govern the observed river runoff. A total of 30 most effective parameters were selected for model calibration as demonstrated in Table 3-1. The model performance was evaluated by statistical indicators such as R^2, NSE, and RSR as given in Table 3.2, and simulated flow results are demonstrated by Figure 3-1.

Table 3-1: Parameters sensitive to river runoff and their fitted values

S. No.	Parameters	Min value	Max value	Fitted value for Chakdara
1	CNOP{..}.mgt	0	100	19.22

2	CN2.mgt	35	98	41.89
3	ALPHA_BNK.gw	0	1	0.58
4	REVAPMN.gw	0	500	287.38
5	GWQMN.gw	0	5000	106.9
6	SURLAG.bsn	0.04	24	21.84
7	SLSOIL.hru	0	150	117
8	EPCO.bsn	0	1	0.7
9	SOL_K(..).sol	0	2000	1975.43
10	SFTMP.bsn	-20	20	10.60
11	SMTMP.bsn	-20	20	15.65
12	SMFMN.bsn	0	20	9.46
13	SNO50COV.bsn	0	1	0.43
14	EPCO.bsn	0	1	0.69
15	SOL_AWC(..).sol	0	0.651836	0.52
16	RFINC(..).sub	0	100	87.56
17	SLSUBBSN.sub	10	150	71.53
18	TMPINC(..).sub	0	100	63.50
19	RCHRG_DP.gw	0	1	0.11
20	DEEPST.gw	0	50000	5373
21	LAT_TTIME.hru	0	180	70.22
22	CH_N2.rte	-0.1	0.3	0.10
23	OV_N.hru	0.01	30	0.56
24	CANMX.hru	0	100	54.32
25	ESCO.hru	0	1	0.83
26	EPCO.hru	0	1	0.70
27	GW_REVAP	0	1	0.10
28	ADJ_PKR	0	1	0.96
29	TIMP	0	1	0.79
30	SNOCOVMX	0	500	423

Table 3.2: Statistical indicators for SWAT model calibration and validation

Watershed	Calibration			Validation		
	NSE	R^2	RSR	NSE	R^2	RSR
Chakdara	0.43	0.50	0.84	0.43	0.51	0.84

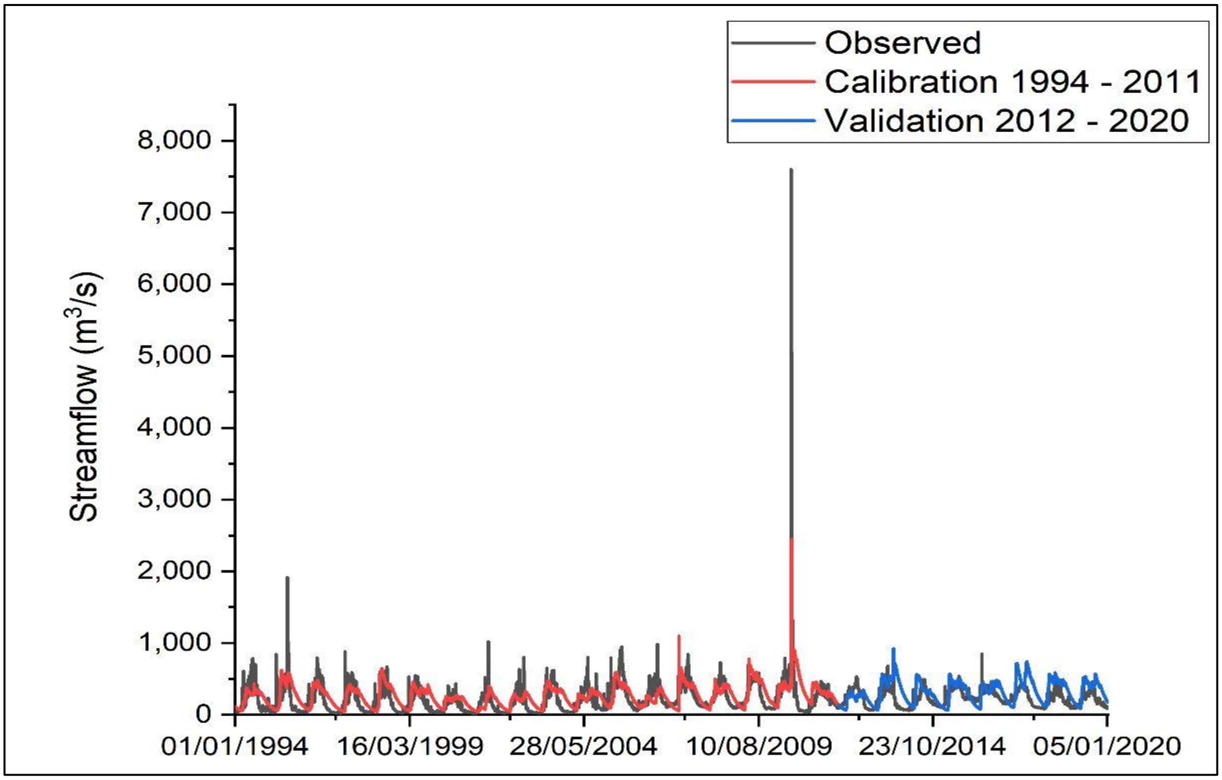

Figure 3-1: SWAT model daily streamflow calibration and validation results at Chakdara station.

3.2 Impact of Climate Change on River Runoff

The SWAT model was used to assess the influence of climate change, i.e., precipitation and temperature (minimum and maximum) on the streamflow using selected MMEs out of 11 GCMs. Figures 3.2 and 3.3 shows the projected streamflow for the next 15 years under SSP245 and SSP585 scenarios at Chakdara station where remarkable increase is observed in future streamflow. The increase in futuristic streamflow is due to increase in air temperature and precipitation in the study area.

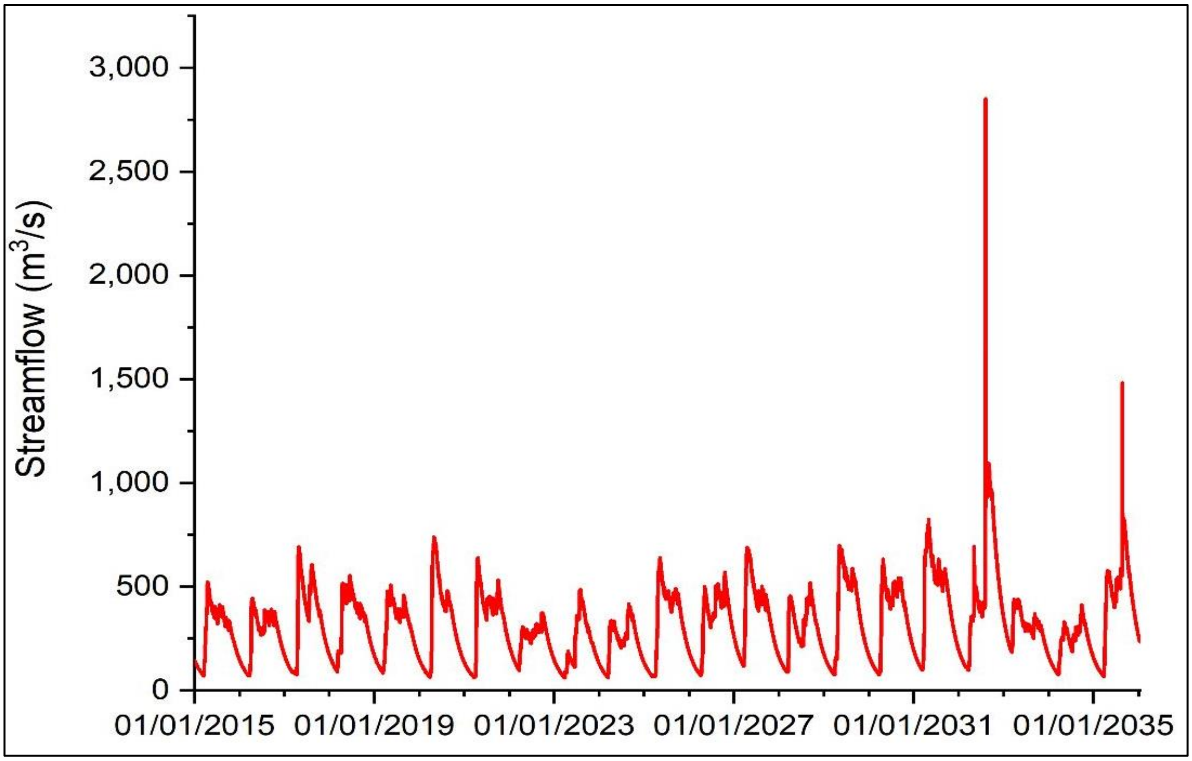

Figure 3-2: SWAT model monthly futuristic streamflow results at Chakdara station for the selected MMEs out of 10 GCMs under SSP245 scenario.

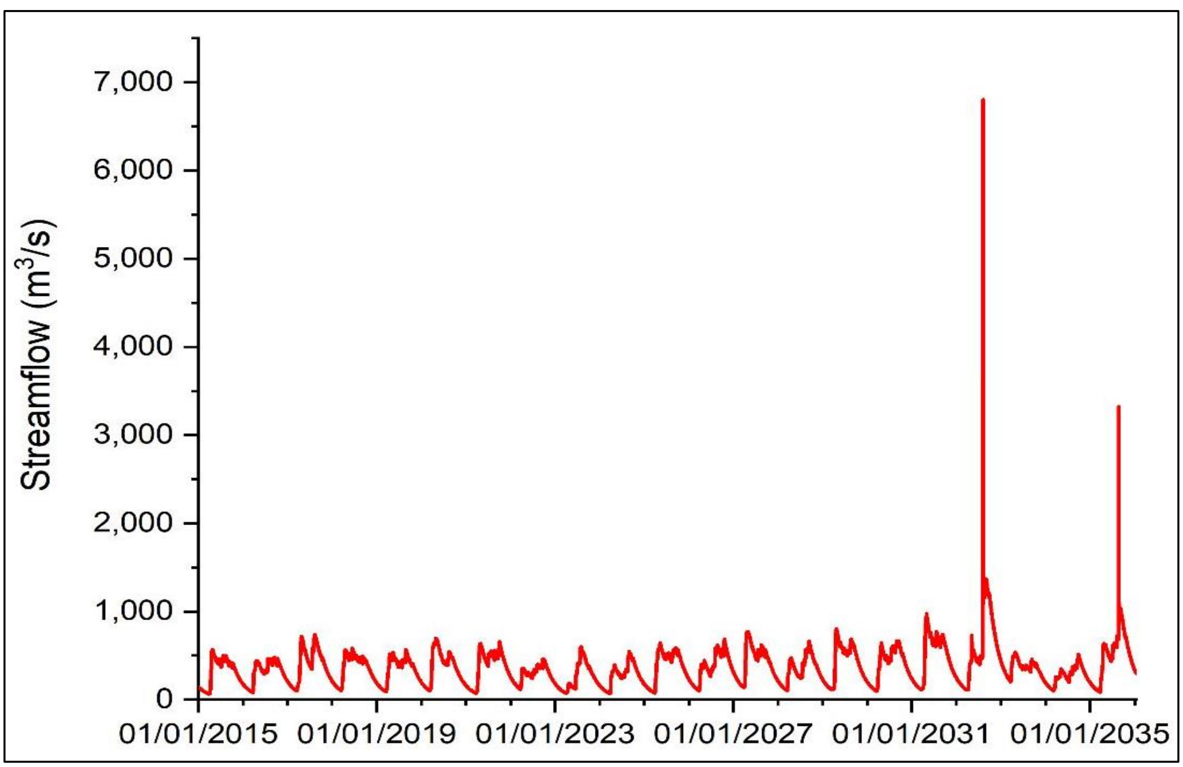

Figure 3-3: SWAT model monthly futuristic streamflow results at Chakdara station for the selected MMEs out of 10 GCMs under SSP585 scenario.

3.3 Flood Frequency Analysis

In the flood frequency analysis, first the comparison of the analysis is done for the control station i.e., Chakdara, followed by flood frequency analysis for the project locations based on the predicted flow under two climate change scenarios. Log-Pearson Type III Distribution has been used for flood frequency analysis of all the stations for different return periods.

3.3.1 Historic and Projected Flood Frequency Analysis at Chakdara

Return levels for 50, 100, 200 and 500 years return periods at Chakdara station based on historic data and projected flow for the selected MMEs out of 10 GCMs under SSP245 and SSP585 scenarios were computed using Gumbel Distribution. The results are presented in Figure 3-4.

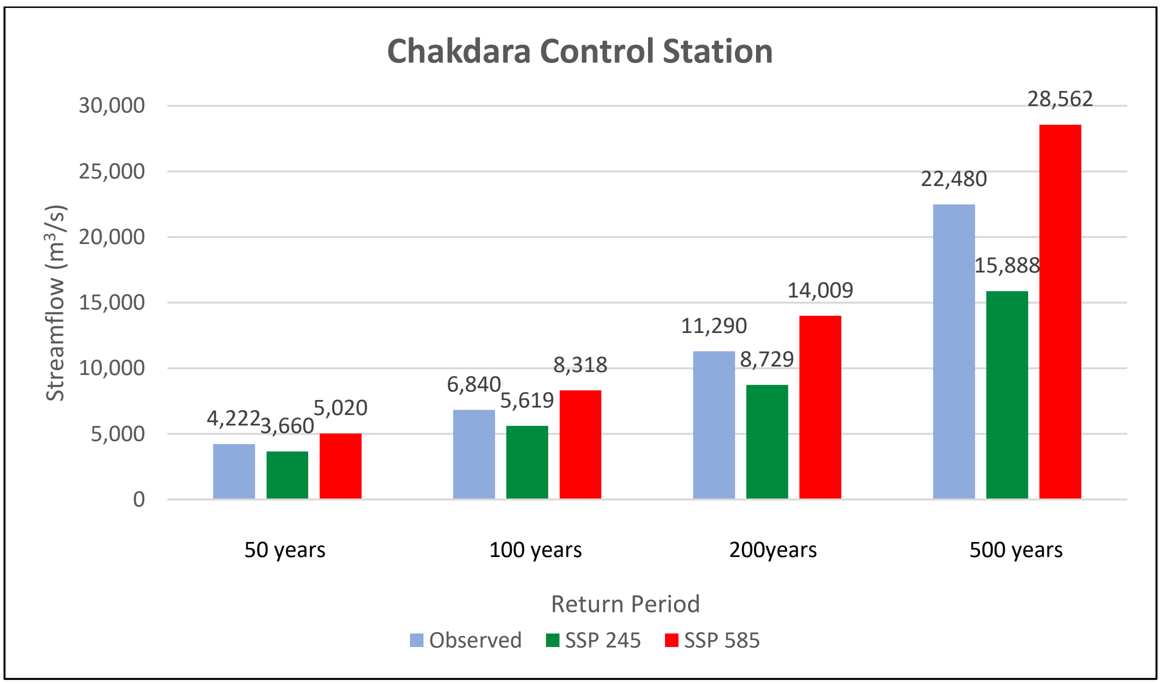

Figure 3-4: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP585 scenarios using SWAT model.

The analysis shows that for SSP585 scenario, higher flows are expected for all the returns periods as compared the results based on historic results (1993-2022). For SSP245 lower flows are expected for all return periods as compared to the historic results. Flow for

SSP245 has a decreasing trend at the station as compared to the base period of 1993 – 2022. This could be because the region has already been experiencing the impact of climate change in the last few decades. Additionally, the higher emissions in SSP585 could lead to more rapid melting of snow and glaciers in the mountains, which could also contribute to higher streamflow spikes.

3.3.2 Flood Frequency Analysis at the Project Locations

Flood frequency analysis for all the project locations was performed and flood flows for return periods of 10, 50, 100, 200 and 500 years were obtained using Log-Pearson Type III Distribution. The floods flow for all the return periods were obtained under both the scenarios i.e., SSP245 and SS585. For all the locations and return periods, the flows are significantly higher for SSP585 as compared to SSP245.

3.3.2.1 Swat

Peak floods for various return periods for project location in Swat were computed that are presented in Table 3-2 and Figure 3-5 to Figure 3-10.

Table 3-2: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model – Swat

Station	SSP Scenario	Flood (cumecs)			
		50 years	100 years	200 years	500 years
Koz Lalko Steel Bridge	SSP 245	49	75	116	212
	SSP 585	67	111	187	381
Nokhara Steel Truss Bridge	SSP 245	70	107	167	304
	SSP 585	96	159	268	546
Baleer Kas Steel Bridge	SSP 245	59	91	141	256
	SSP 585	81	134	226	461
Mashkomai Bridge	SSP 245	31	47	73	134
	SSP 585	42	70	118	240
Ayub Prestressed Bridge	SSP 245	2,882	4,425	6,874	12,511
	SSP 585	3,953	6,550	11,032	22,492
Keeba Mankial Pedestrian Suspension Bridge	SSP 245	1,556	2,388	3,710	6,753
	SSP 585	2,134	3,535	5,954	12,140

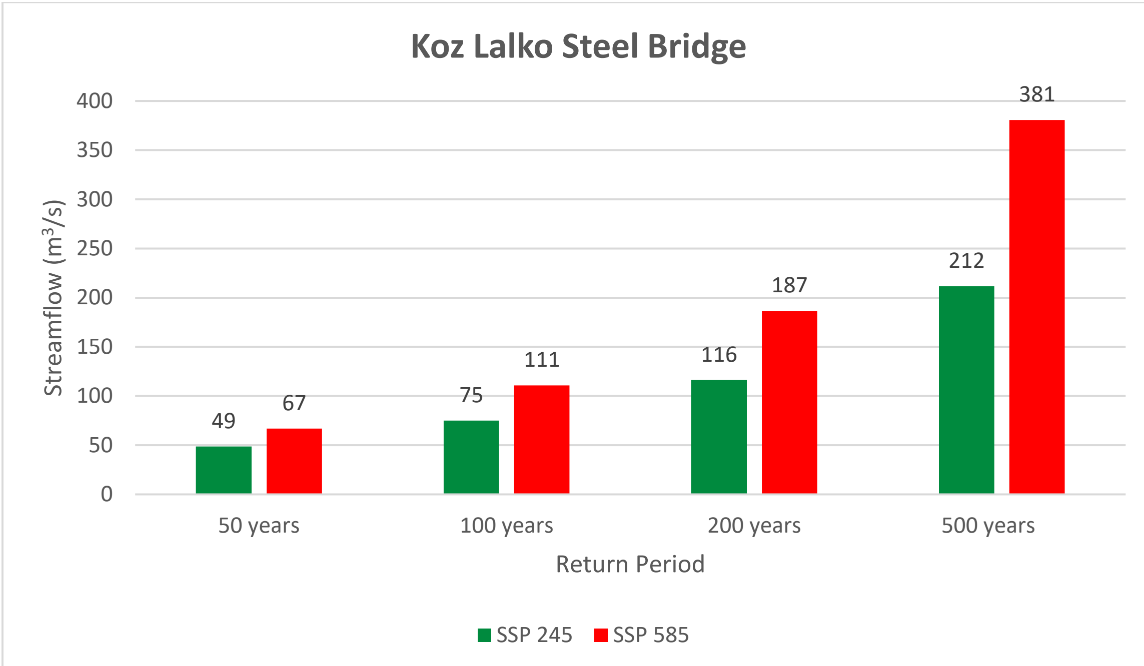

Figure 3-5: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

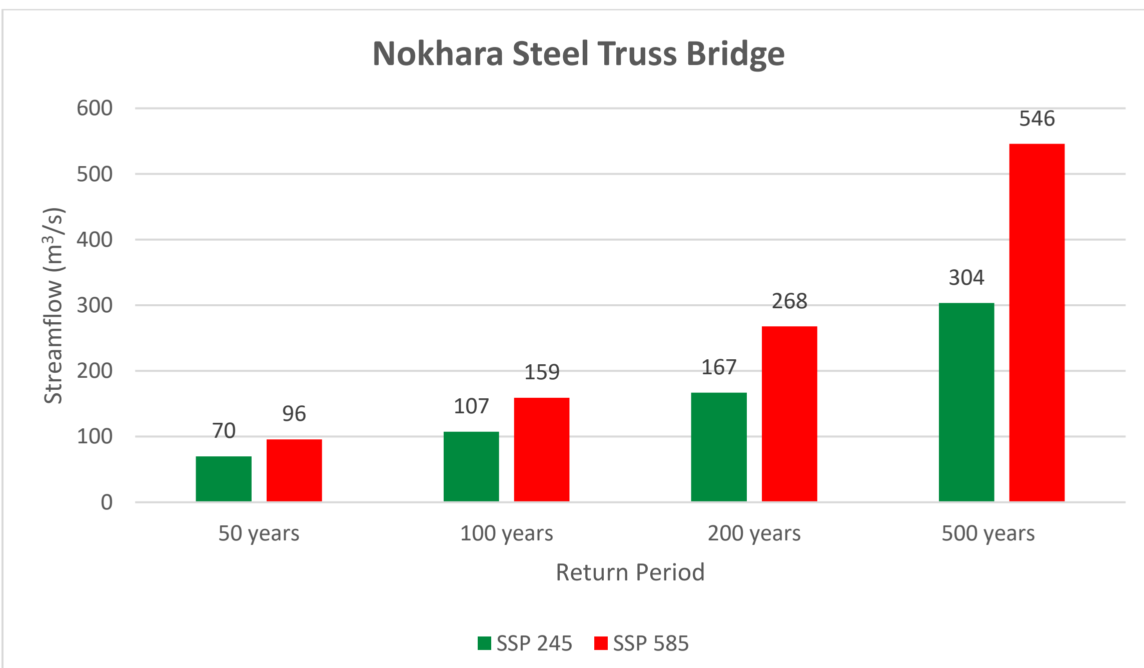

Figure 3-6: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

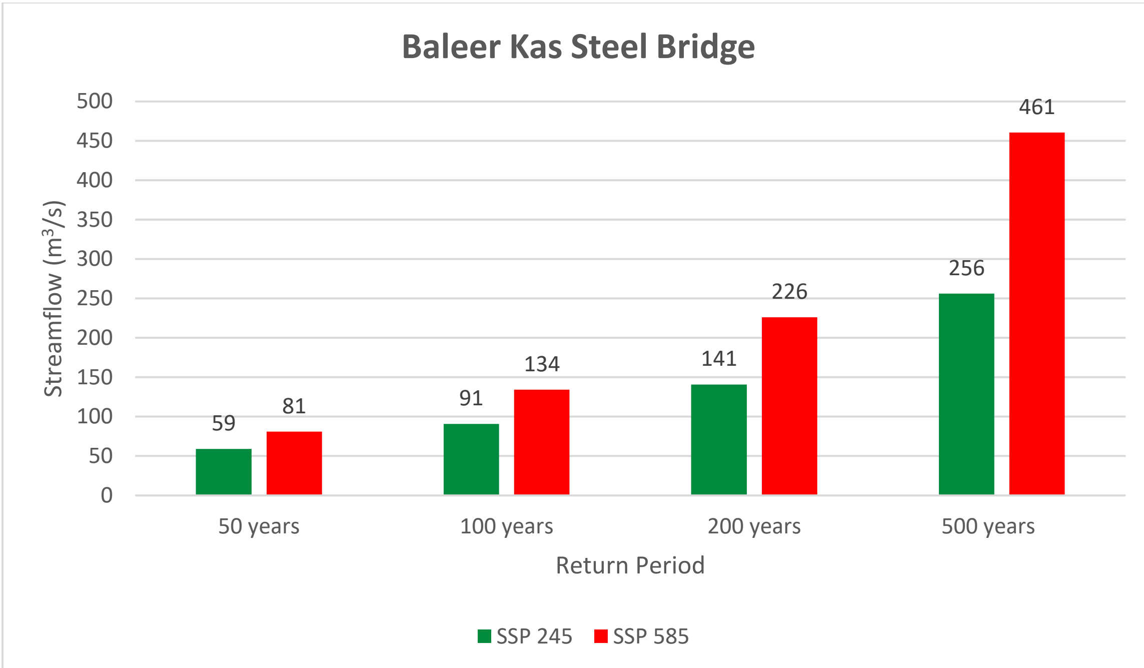

Figure 3-7: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

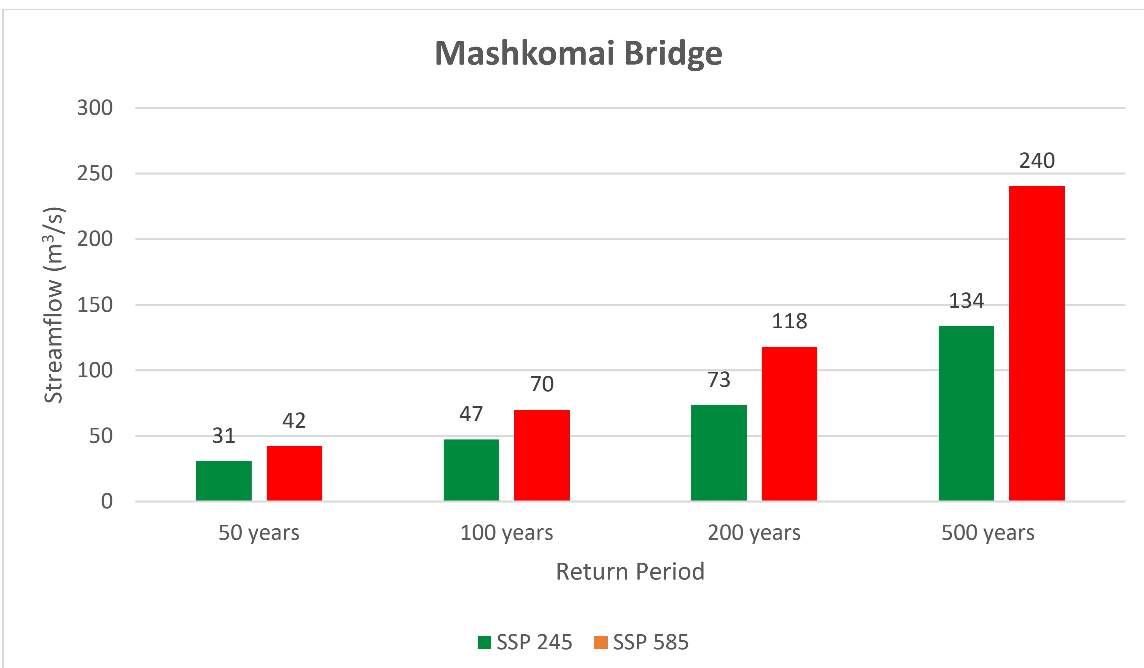

Figure 3-8: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

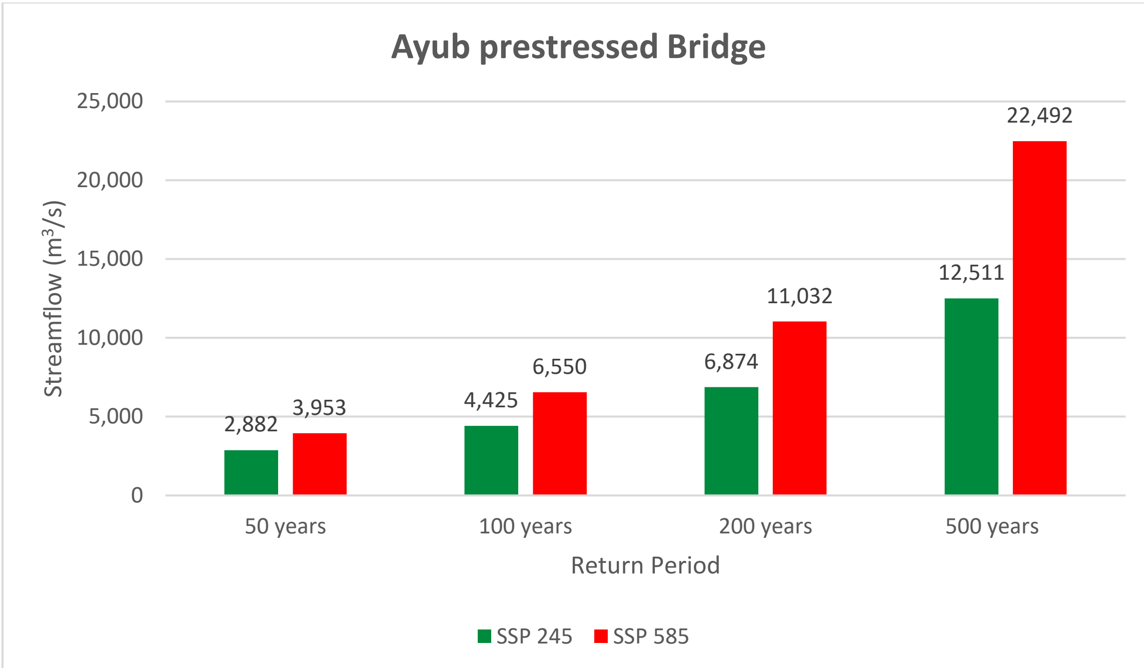

Figure 3-9: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

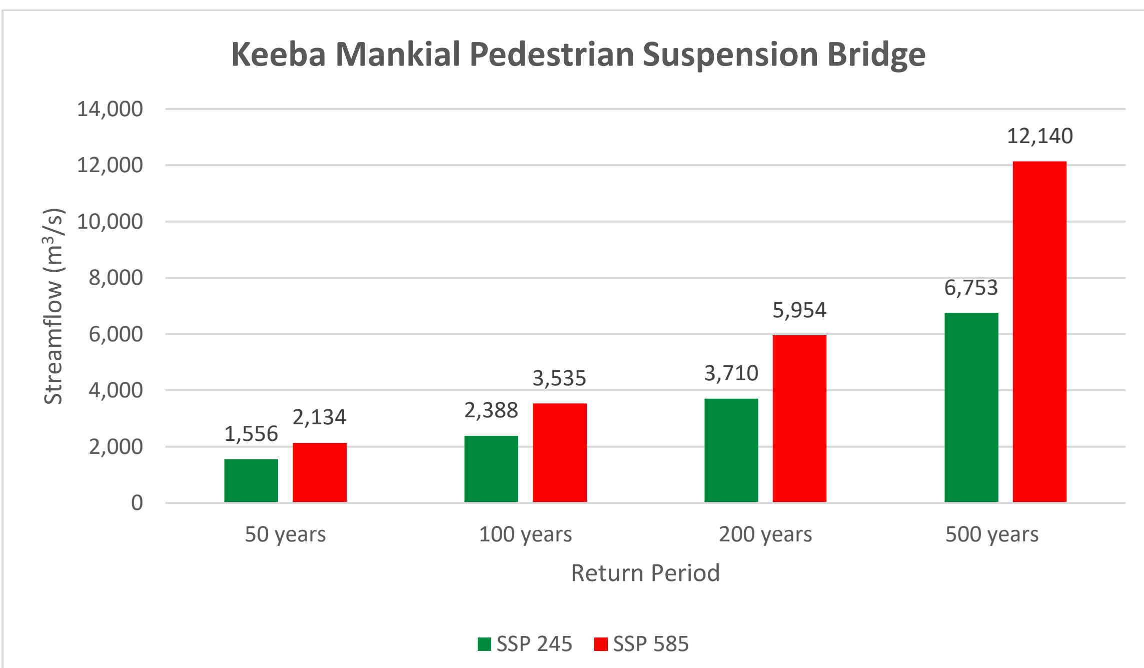

Figure 3-10: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

3.3.2.2 Lower Dir

Peak floods for various return periods for project location in Lower Dir were computed that are presented in Table 3-3 and Figure 3-9 to Figure 3-14.

Table 3-3: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model – Lower Dir

Station	SSP Scenario	Flood (cumecs)			
		50 years	100 years	200 years	500 years
Malakabad suspension Bridge	SSP 245	2,314	3,553	5,519	10,046
	SSP 585	3,174	5,259	8,858	18,060
Sacha and Maira Bridge	SSP 245	2,414	3,707	5,758	10,481
	SSP 585	3,311	5,487	9,241	18,841
Khal Japani Plate GirderBridge	SSP 245	2,396	3,679	5,715	10,403
	SSP 585	3,287	5,446	9,172	18,701
University of Malakand Bridge	SSP 245	3,473	5,331	8,282	15,075
	SSP 585	4,763	7,892	13,292	27,100

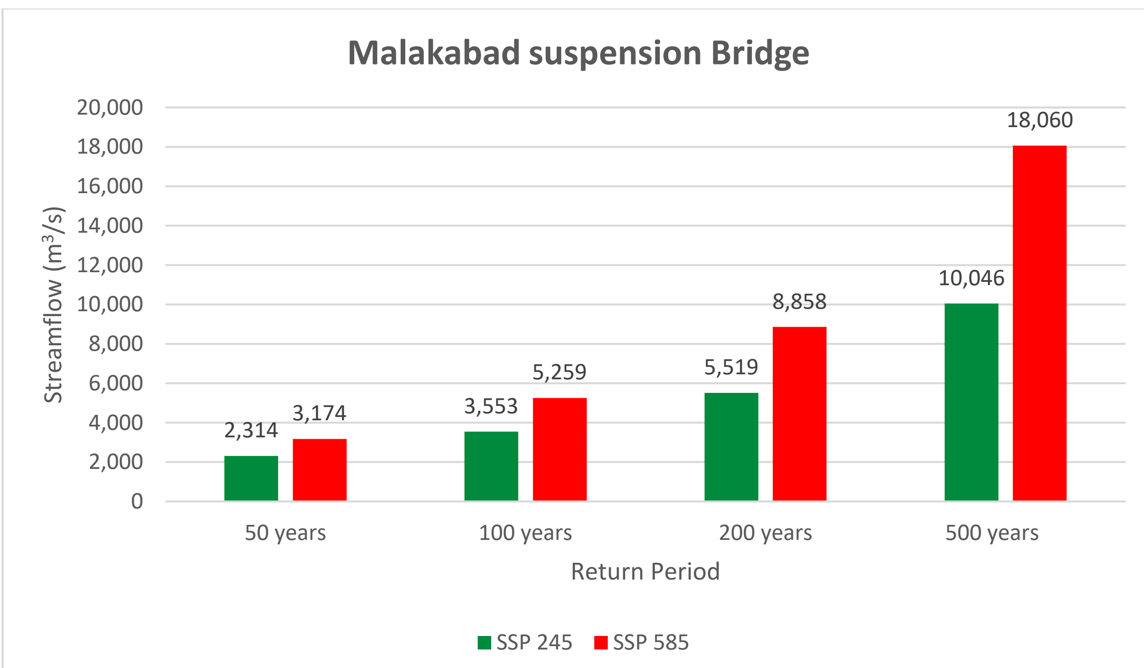

Figure 3-11: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

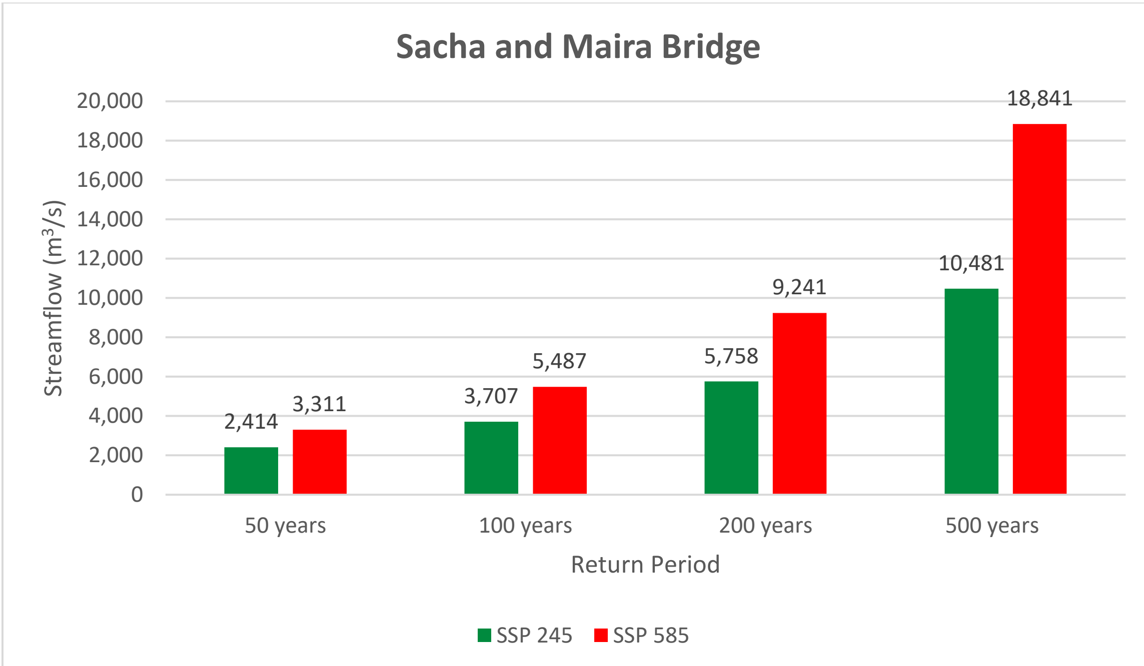

Figure 3-12: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

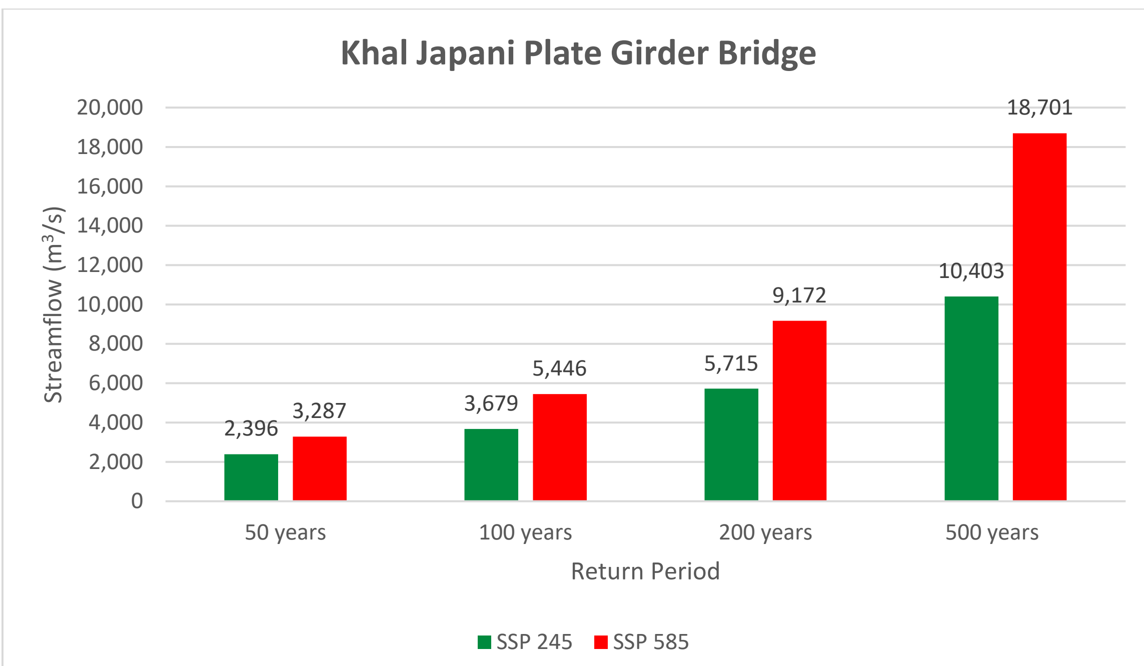

Figure 3-13: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

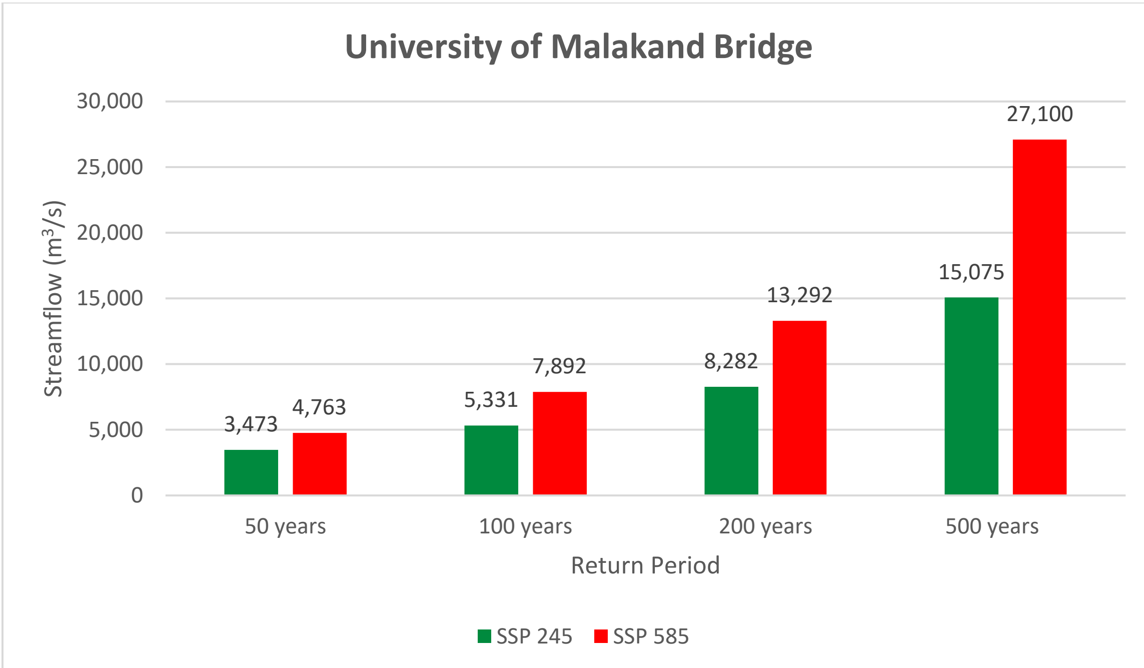

Figure 3-14: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

3.3.2.3 *Charsadda*

Peak floods for various return periods for project locations in Charsadda were computed that are presented in Table 3-4 and Figure 3-15 to Figure 3-19.

Table 3-4: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model – Charsadda

Station	SSP Scenario	Flood (cumecs)			
		50 years	100 years	200 years	500 years
Tangi Bazar Culvert	SSP 245	10	11	12	13
	SSP 585	12	13	14	15
Jura Bridge	SSP 245	5	6	7	8
	SSP 585	7	8	10	12
Culvert (A) on Tarkha	SSP 245	17	20	23	28
	SSP 585	19	22	26	32
Culvert (B) on Tarkha	SSP 245	17	20	23	28
	SSP 585	19	22	26	32
Tarkha Culvert at Haji Zai	SSP 245	5	5	6	6
	SSP 585	5	6	6	7

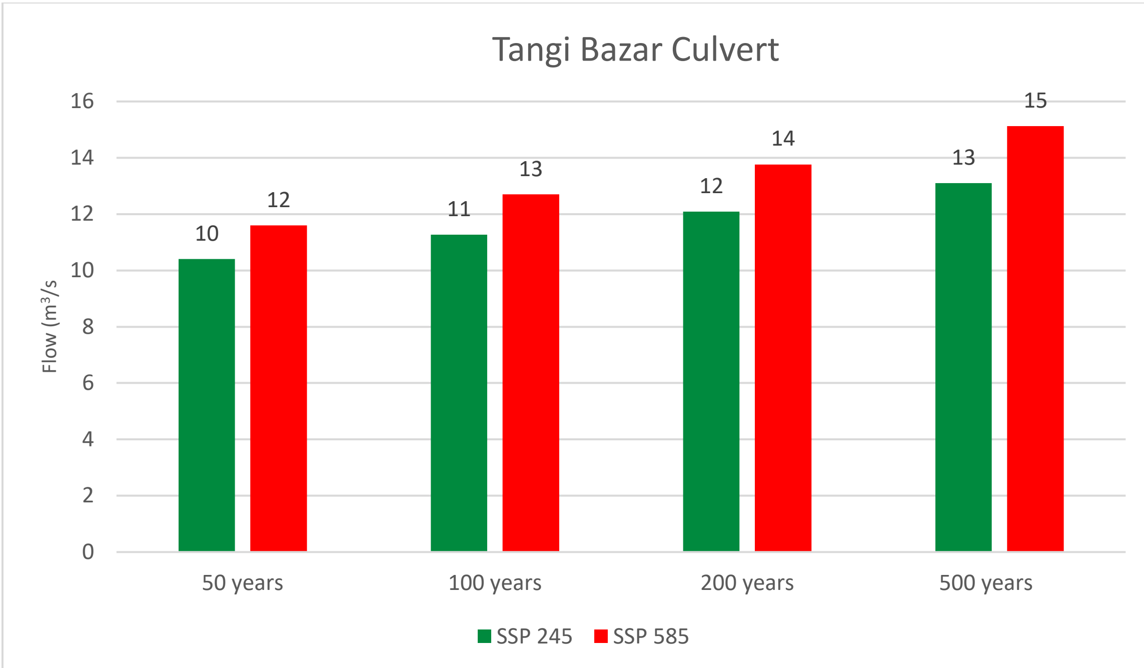

Figure 3-15: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

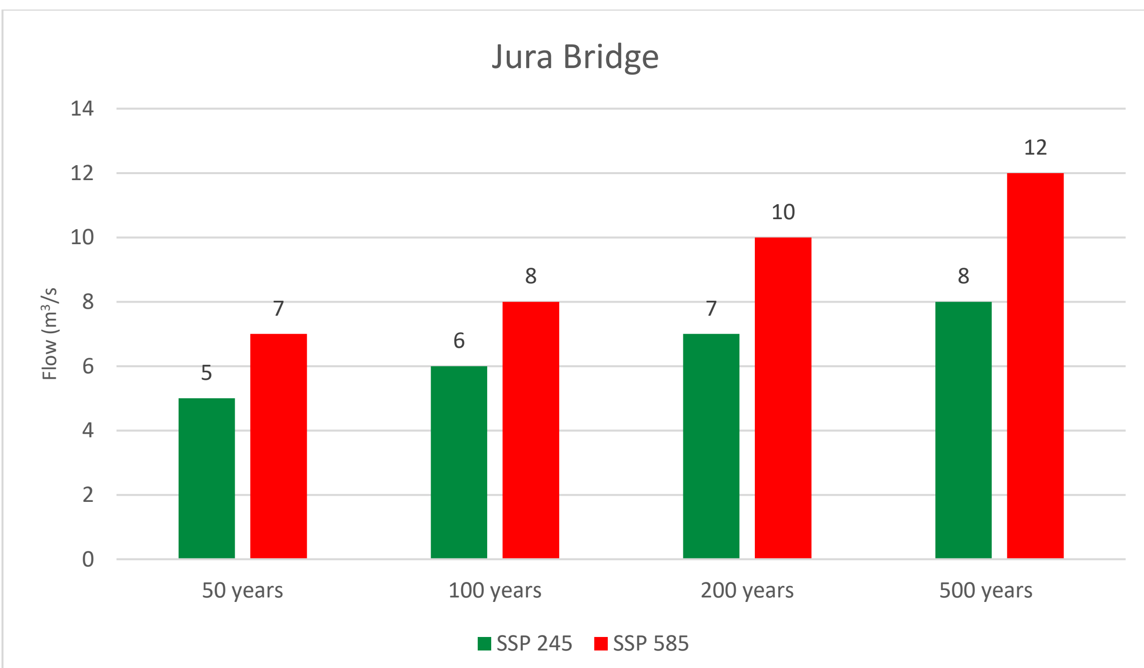

Figure 3-16: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

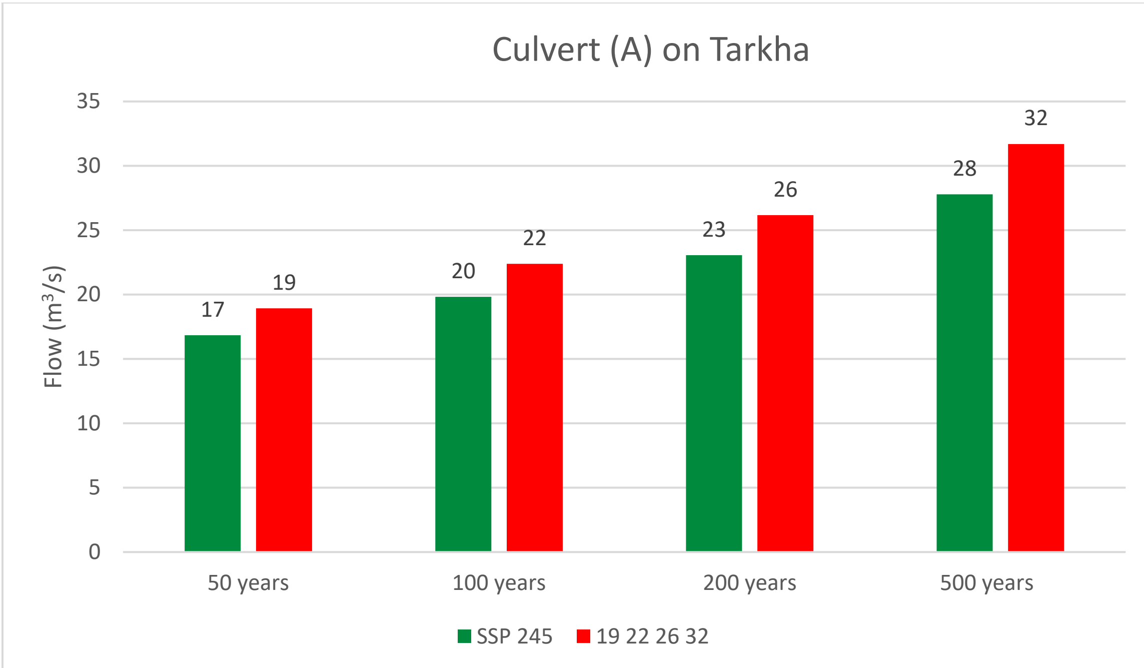

Figure 3-17: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

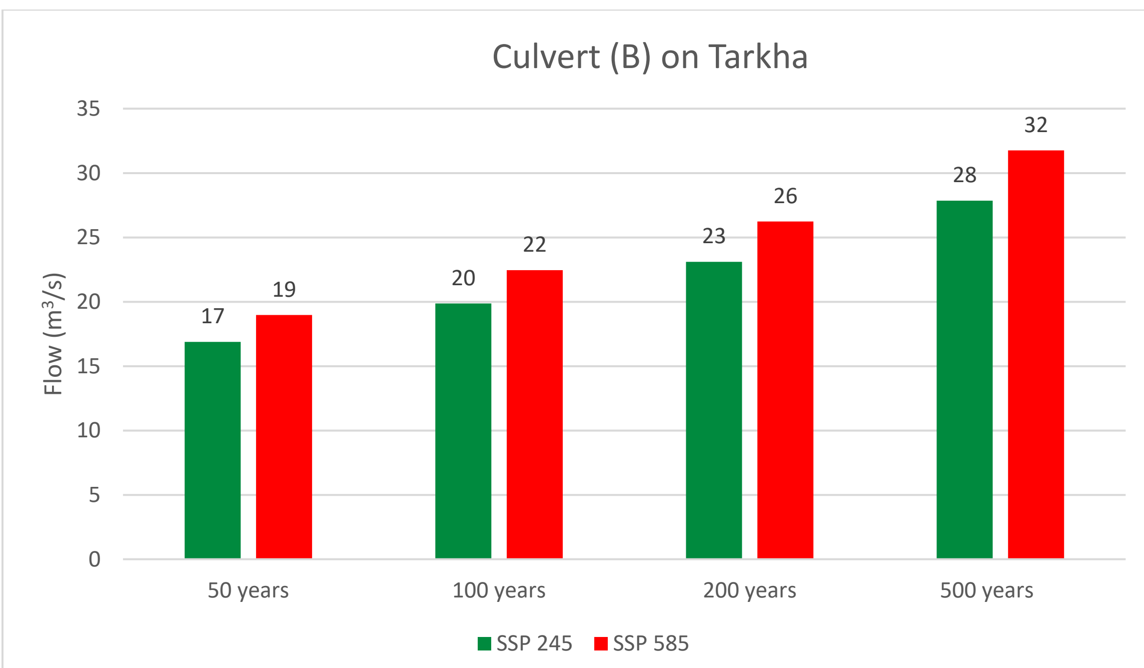

Figure 3-18: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

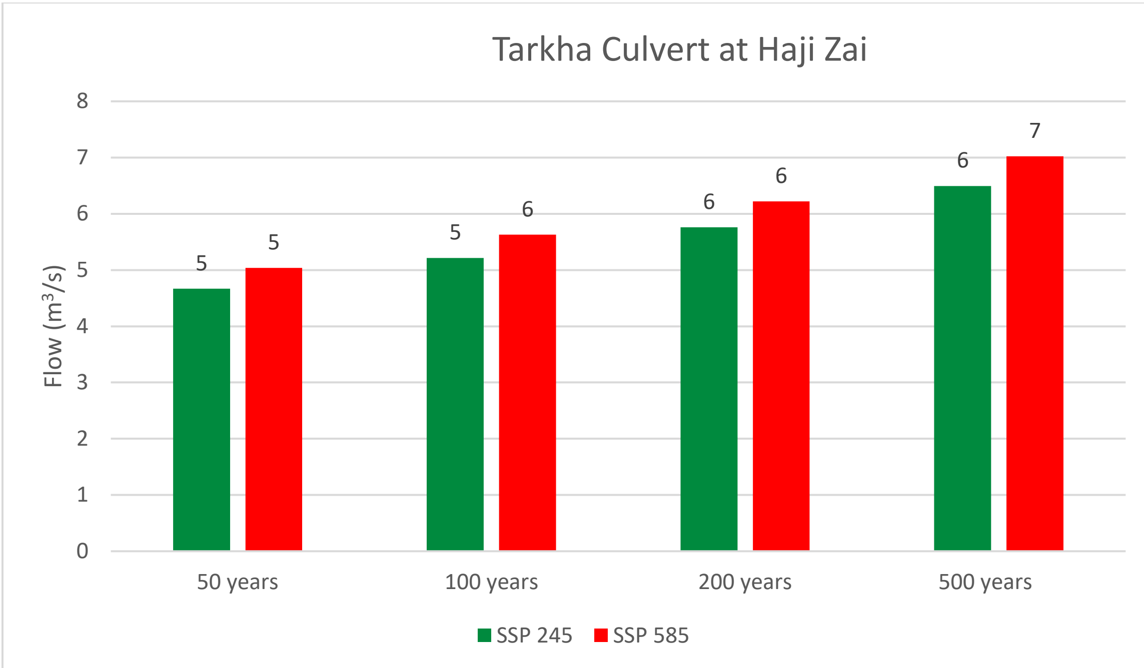

Figure 3-19: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

3.3.2.4 Nowshera Region

Peak floods for various return periods for project location in Nowshera were computed that are presented in Table 3-5 and Figure 3-20.

Table 3-5: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model – Nowshera

Station	SSP Scenario	Flood (cumecs)			
		50 years	100 years	200 years	500 years
Muhib Banda Village Road	SSP 245	8	9	10	11
	SSP 585	9	10	11	12

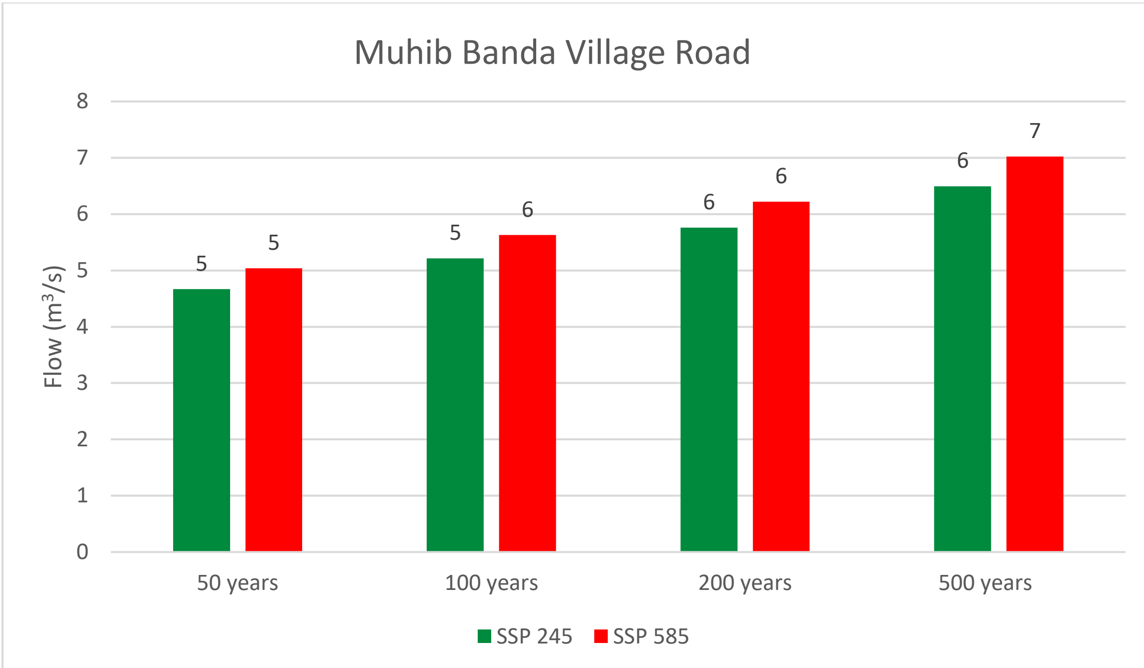

Figure 3-20: Flood return periods for 50, 100, 200 and 500 years for the selected MMEs out of 10 GCMs under SSP245 and SSP 585 scenarios using SWAT model.

3.4 Selection of Scenario

In this study two SSP scenarios have been considered out of the five discussed in section 2.1 that are:

- SSP 245
- SSP 585

The Intergovernmental Panel on Climate Change (IPCC) Sixth report did not estimate the likelihoods of the scenarios. However, a 2020 commentary published in Nature describes that:

- SSP58.5 as highly unlikely,
- SSP37.0 as unlikely, and
- SSP24.5 as likely[9].

[9] Hausfather, Zeke; Peters, Glen P. (2020-01-29). "Emissions – the 'business as usual' story is misleading". *Nature*. 577

Another report citing the above commentary shows that RCP8.5, which is replaced by SSP 585, is the best match to the cumulative emissions from 2005 to 2020[10]. (R. Schwalm – 2020).

In the light of the above-mentioned studies, it is difficult to decide the option of a particular SSP. The selection of a particular scenario should be based on the following parameters:

- Climate Risk Vulnerability
- Economy

The climate risk vulnerability for countries has been defined by many studies. Results of one such study defining climate risk index for countries globally are shown in Figure 3-21.

A higher vulnerability would need the consideration of SSP 585 that is to be prepared for the worst-case scenario because of vulnerability to high risks. Countries with lower vulnerability risk may opt for SSP245 scenario while planning and designing their infrastructure.

The study shows that Pakistan has been the eighth most affected country. Particularly the northern parts of the country that includes the current study areas, would be hit hard by the effects of climate change. In this perspective, considering SSP585 scenario for planning and designing of infrastructure is highly desirable.

[10] Schwalm, Christopher R.; Glendon, Spencer; Duffy, Philip B. (2020-08-03). "RCP8.5 tracks cumulative CO2 emissions". *PNAS*. 117 (33)

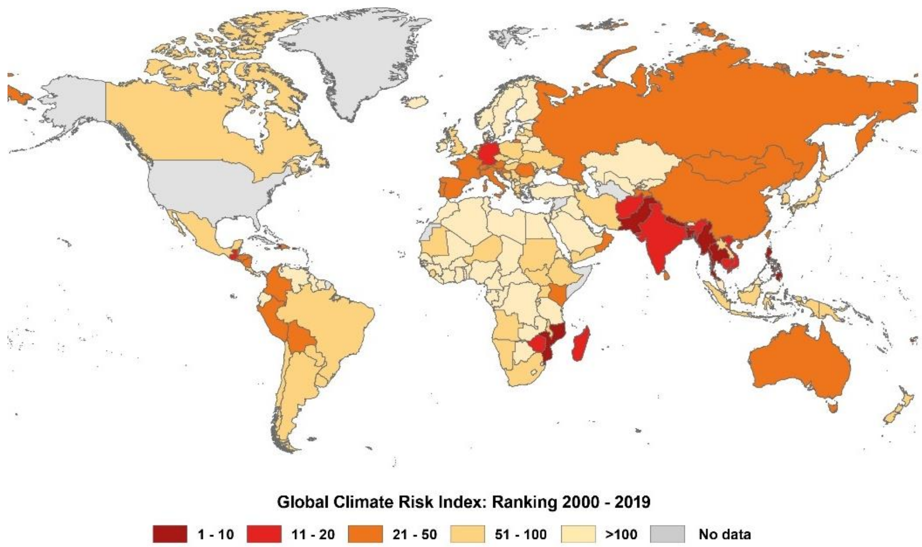

Figure 3-21: Climate risk vulnerability index by country[11] (Source: GermanWatch)

One the other hand while considering economy, it should be noted that consideration of worst-case scenario of SSP585 would require higher budgets as compared to SSP245. Careful evaluation of the difference in terms of finances needs to be done. In some cases, the gap would be too high and consideration of SSP585 would lead to financial nonviable infrastructure – in such cases opting for SSP245 or even using historic data could be the choice. In cases where the financial evaluation leads to a narrow and affordable gap between the scenarios, SSP585 scenario should be opted for planning of designing of infrastructure.

In a nutshell, from the above discussion, it cannot be concluded to recommend a generic scenario i.e., SSP 245 or SSP585. However, Pakistan being one the most vulnerable country to climate change, efforts should be made to make the infrastructure resilient for the worst-case scenario of SSP585 but being a developing country considerable consideration to the financial implication need to be given alongside. Beside these aspects, the type of infrastructure and its importance also need to be carefully evaluated in the selection of a particular SSP.

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[11] GermanWatch: Global Climate Risk Index 2021

4 Conclusions and Recommendations

Detailed climate change inclusive hydrological study of the Swat River basin, that included four study areas of the project i.e., Swat, Lower Dir, Charsadda and Nowshera, was carried out considering meticulous and detailed climate change predictions. The purpose was to provide hydrological inputs in the planning and design of climate resilient roads and bridges that were damaged/affected in the recent 2022 floods.

The latest available tools including general circulation models (GCMs) based on CMIP6 and tools available for bias correction have been used to predict climate parameters in the study area - GCMs are computer driven models used for projecting climate change while CMIP6 is the latest version of GCM models. Climate data sets comprising of daily minimum and maximum temperatures, precipitation, and stream discharge for 30 years (1993–2022) were acquired from their official custodians i.e., Pakistan Meteorological Department and WAPDA. Two social-shared pathways (SSP) scenarios of SSP245 and SSP585 were used in the study. For simplicity the former can be called an optimistic scenario while the latter as the Worst-case scenario.

Several hydrological models including, models based on artificial intelligence and machine learning, and semi-distributed model of SWAT, were evaluated for the study basin – SWAT (Soil and Water Conservation Tool) is a model used to simulate the quality and quantity of surface and ground water. The SWAT hydrological yielded good statistical performance indicators during calibration and validation (comparison of simulated and historical data) and hence was used for evaluation of flow in various streams/rivers of the study area. Based on the stream flows thus evaluated, floods corresponding to 50, 100, 200 and 500 years return periods were estimated.

4.1 Conclusions

Overall, the following conclusions are drawn from the study:

- There is an increasing trend in both maximum and minimum daily temperature, averaged annually. The overall mean temperature has an increasing trend. These observations are true for all regions of the study area (Swat, Lower Dir, Charsadda and Nowshera) and for both the considered SSP scenarios.
- The rate of increase in (minimum and maximum) temperatures is almost twice as high in SSP585 (Worst-case) scenario compared to that in SSP245 (Optimistic).
- The mean annual precipitation shows extremely low variation over the next fifteen years. However, rising temperatures cause increased snow melts which combined with intensified daily precipitations, resulting in larger stream flows.
- For the Swat and Dir regions, the rise in maximum temperature is projected to be 2.77 °C and 5.77 °C under SSP245 (Optimistic) and SSP585 (Worst-case) scenarios respectively, by the end of the century. Similarly, an increase in the minimum temperature is projected to be 2.53 °C and 5.70 °C under SSP245 (Optimistic) and SSP585 (Worst-case) scenario respectively, over the same period.
- For the Charsadda and Nowshera regions, the rise in maximum temperature is projected to be 2.81 °C and 5.78 °C under SSP245 (Optimistic) and SSP585 (Worst-case) scenarios respectively, by the end of the century. Similarly, an increase in the minimum temperature is projected to be 2.54 °C and 5.62 °C under SSP245 (Optimistic) and SSP585 (Worst-case) scenario respectively, over the same period.
- Stream flows were estimated at Chakdara as control station. The peak floods at the station declined by 13%, 18%, 23% and 30% for 50, 100, 200 and 500-year return periods respectively compared to the peak floods based on historic data under the SSP245 (Optimistic) scenario while the same increased by 19%, 22%, 24% and 27% for 50, 100, 200 and 500-year return periods respectively under the SSP585 (Worst-case) scenario.

4.2 Recommendations

- It is recommended to consider the SSP585 (Worst-case) scenario for planning and designing of all major and critical infrastructure.

- Climate change modelling should be a pre-requisite for planning, design, and implementation of all new major infrastructure as well as involving major rehabilitation.
- The government must take lead on extensive flood plain mapping, accounting for climate change, of all the major rivers – corresponding to various flood return periods - in the province which should then form a basis for land use planning, and siting of public infrastructure assets. Section 3.(1).(a) of the KP River Protection Ordinance 2002 may be amended to appropriately cover this recommendation.
- Based on analysis of floods with different return periods estimated at different sites (Swat, Lower Dir, Charsadda and Nowshera) for SSP245 (Optimistic) and SSP585 (Worst-case), whereupon it has been revealed that SSP585 has much more severe design demand as compared to SSP245. It is therefore recommended to select floods for design of bridges based on SSP585 with regard to Bridge Scour, Design Flood and Check Flood.