HYDROLOGICAL RESPONSE TO CLIMATE CHANGE ON SOAN RIVER CATCHMENT

A Thesis submitted in partial fulfillment
of the requirements for the degree of

Master of Science
in
Water Resources Engineering and Management

By

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THESIS ACCEPTANCE CERTIFICATE

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Date __________________________________

Disclaimer

The views expressed in this work are those of the creators and do not necessarily represent those of the UK Government's Department for International Development, the International Development Research Centre, Canada or its Board of Governors.

Dedication

I dedicate this research to my parents

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(Maria Javed)

ABSTRACT

Freshwater “inadequacy” and security have been determined to be chief global environmental problems of 21st century. Pakistan is considered as “water stressed” country in the world. About 65% of the region in Pakistan is covered by Indus river basin. For viable water resources, it is important to understand the repercussions of climate change and how this change effect water resources at basin scale and their utilization for green growth. Soan River catchment has been playing a vital role for developing water resources for the twin cities and Chakwal for the past many years. Satellite imagery was utilized for land cover classification and to investigate the land use changes in the Soan catchment, using an image processing software Earth Recourses Data Analysis System (ERDAS). The hydrological models were calibrated by using observed daily stream flows of 4 years (2007–2010), while validated for 3 years (2011–2013). Climate change projected precipitation data derived under the medium and high emission scenarios namely RCP 4.5 and RCP 8.5, respectively, was extracted for Soan river catchment from dataset developed by “Himalayan Adaptation Water and Resilience (HI-AWARE)” for “Indus, Ganges and Brahmaputra (IGB)” River basins. Bias correction of projected data was performed using delta technique and corrected daily precipitation data was applied as input of validated HEC-HMS model to check the hydrological response of catchment for future climate change conditions. For ease of understanding, analyses were carried out for three future time windows named as 2025s (2010-2040), 2055s (2041-2070) and 2085s (2071-2100). Results showed increase in built-up and urbanized area and water bodies throughout the catchment. Analysis of HI-AWARE Climate dataset based on 8 GCMs statistically downscaled at 10 km x 10 km resolution spatial grid showed overall increase in precipitation at all the 11 stations under both scenarios RCP45 and RCP 85. Both scenarios RCP45 and RCP 85 indicate the potential increase in stream flows at Dhok Pathan that could considerably lead to raise the water resources of the catchment under the changing climate during the century. So, large and small storage reservoirs are essentially required to manage and cater the flood conditions in Soan River catchment.

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LIST OF ABBREVIATIONS

IWT	Indus Waters Treaty
IBIS	Indus Basin Irrigation System
LiDAR	Light Detection and Ranging
GIS	Geographic information System
HEC-HMS	Hydrological Engineering Center– Hydrological Modeling System
ASTER	Advance Space–borne Thermal Emission and Reflection Radiometer Global
GDEM	Digital Elevation Model
AOGCM's	Atmosphere-Ocean Global Circulation Models
GCM	Global Climate Model
RCP	Representative Concentration Pathways
GHG	Green House Gases
AR5	Assessment Report- 5
IPCC	Intergovernmental Panel on Climate Change
ECP	Extended Concentration Pathway
PMP	Probable Maximum Precipitation
PMF	Probable Maximum Flood
WEB-DHM	Water and Energy Budget-Based Distributed Hydrological Model
PGB	Poorly Gaged Basin
TM	Thematic Mapper
ETM	Enhanced Thematic Mapper
SWAT	Soil & Water Assessment Tool
NS	Nash Sutcliff coefficient
RMSE	Root Mean Square Error

PMD	Pakistan Meteorological Department
WAPDA	Water and Power Development Authority
SDO	Small Dams Organization
NARC	National Agriculture Research Centre
CDA	Capital Development Authority
SWHP	Surface Water Hydrology Project
m.a.s.l	Meter Above Sea Level
CN	Curve Number
SCS	Soil Conservation Service
ERDAS	Earth Recourses Data Analysis System
DEM	Digital Elevation Model

CHAPTER 1

INTRODUCTION

1.1 General

Freshwater "inadequacy" and security have been determined to be chief global environmental problems of 21st century. But it is unusually difficult to specify the type of global water crisis which the world is facing right now (Srinivasan et al., 2012) despite the global population is estimated to rise to about 9 billion by 2050 (Gleick and Palaniappan, 2010).

In hydrologic cycle, the earth has considerable water reserves in many forms and characteristics in different stock and flow. The earth has a stock of roughly 1.4 billion cubic kilometers of water, the major portion of which exists in the form of salt water (nearly 97%) found in the oceans. The fresh water stock of the work which is limited is estimated to be around 35 million cubic kilometers. Most of the fresh water that exists is out of reach of humans. It either exists in the shape of glaciers in Antarctica and Greenland, Long lasting continuous snow cover or in deep ground water out of reach of humans. Only a small portion of fresh water is accessible in the form of river flows, securable surface lakes and ground water, soil moisture or rainfall. (Shiklomanov, 2000)

Pakistan is considered as "water stressed" country in the world as stated by World Bank and Asian Development Bank due to which Pakistan will experience acute shortage of water for the purpose of irrigation, industry and for human use over the coming 5 years. (Asim et al., 2012)

About 65% of the region in Pakistan is covered by Indus river basin which is approximately 520000 km2. This basin covers the entire province of Khyber Pakhtunkhwa, most of area of province Sindh, Punjab and Baluchistan's eastern part. (FAO, 2011)

The water to the Indus river is supplied by the glaciers of Hindu Kush and Karakoram. As Indus river covers 67% of the Pakistan so it is the largest river of Pakistan and main source of fresh water. It supports the 90% agriculture, household and industrial requirements (Khoso et al., 2015)**.** According to the terms agreed by Pakistan and India which is known as Indus Water Treaty (IWT), the water from three eastern river Ravi, Bias and Sutlej India was to utilize the water while Pakistan was to utilize water from three eastern rivers; Indus, Chenab and Jehlum (Asim et al., 2012).

Indus river system is fed by perennial rivers (WCD, 2000), which are helped by different streams/nullahs and small rivers like Kunar, Swat, Haro etc. These small rivers contributr water to the whole Indus Basin Irrigation system for storage of water of river and for the purpose of diversion (NDMAUNDP, 2010).

The IBIS consist of 16 barrages, three reservoirs, two head-works, 12 inter river link canals, two siphons over main rivers, and 44 canal irrigation systems, of which 14 in Sindh, 23 are in Punjab, two in Baluchistan and five in Khyber Pakhtunkhwa (KP) (Van Steenbergen et al., 2015). A lot of intellectuals and economist are of the opinion that if India succeeds in their plan to build dams on rivers Chenab and Ravi then in this case there would be serious ramifications for the agriculture industry of Pakistan as well as it can potentially seriously compromise the national security of Pakistan (Sharif, 2010).

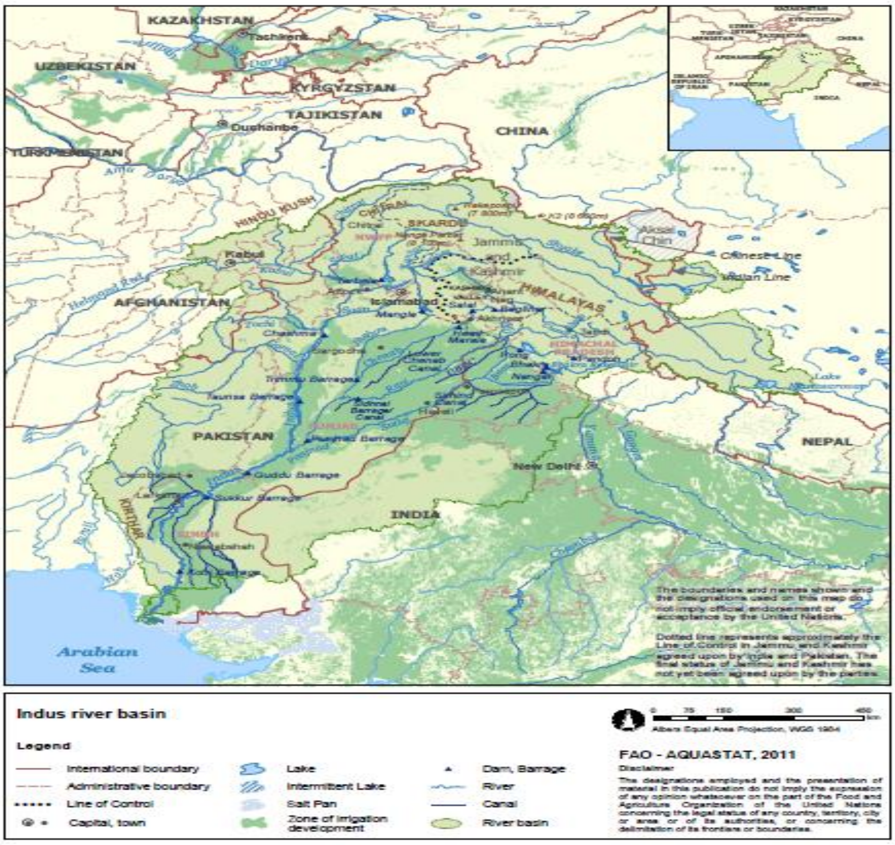


Figure 1-1 Map of Indus Basin (Source: FAO- Aquastat, 2011)

The climate covering the Indus river basin is not uniform. It differs from subtropical arid and semiarid to temperate sub humid on the plains of Punjab and Sindh provinces to alpine in the highlands of the north. Annual precipitation varies between 100 and 500 mm in the plains to a extreme of 2000 mm on hills slopes. The factor that contributes to most of river runoff is snowfall as higher altitudes (above 2500m) (Ojeh, 2006)

Changes in spatiotemporal variations in seasonal cycle, intensity and frequency of highest events have footprint on our essential natural resources. In order for rational water resources, it is important to understand the repercussions of climate variation and how this change effect water resources at basin scale and their utilization for green growth. In recent times, the climate change is having adverse effects around the work as can be seen in the form of flood events. In the current scenario there is need for more robust strategies and risk management plans. (ICE, 2001)

1.2 Problem Statement

The global threat in today's earth is the deterioration of natural resources which is caused by ever expanding human population and changes of lifestyle. Conservation of land and water resources these days are of utmost importance for social and environmental concern (Lal, 2000). In future, it is essential for the operation and planning of hydraulic equipment of water resources in Pakistan under the umbrella of climate change(Akhtar et al., 2008). The sedimentation of reservoirs is primarily caused by surface runoff due to soil erosion. The potential impact of climate change on hydrologic regime in Soan River catchment, Pakistan was explained by water and energy based distributed hydrological model. This model was used to look into intra-basin river runoff. It is a proven fact that in the near future more flood will come due to climate change. In addition to that there is a low chance of drought in Soan river basin in future. In order to reach to more definitive conclusion, a thorough research by integrating hydrological model with socioeconomic model is required to evaluate the track of climate change (Bhatti et al., 2013). To investigate the local catchment more research is needed.

1.3 Rational of Study

For the contribution to socioeconomic development of the area proper management of watershed is required. In the absence of proper management, these resources will be lost which will have detrimental effect on our lives as well as on environment. Climate change will pave way for meaningful change in spatial and temporal pattern variation in hydrological cycle. This will in turn lead to ensuing water shortage, floods, drought, environmental degradation etc. And it is especially remarkable in semi-humid and semi-arid region (Xia et al., 2012). In terms of population twin cities (Islamabad/Rawalpindi) is fifth populous urban area of Pakistan. It has a population of 2.1 million which comprises of 1.5 million in Rawalpindi and in Islamabad it is 0.6 million (GOP, 2000). Soan River catchment has been playing a vital role for developing water resources for the twin cities and Chakwal for the past many years. Keeping in view of its importance it is essentially required to study the hydrological response of catchment due to climatic change for assessing hydrological situation in future years and planning of adaptation strategies.

1.4 Objective

i. Application of rainfall runoff model to simulate the stream flow of Soan River Catchment.
ii. To investigate the hydrological response to climate changes, for the estimation of future water availability in catchment.

1.5 Scope of Study

This study was first conducted to investigate the land use/cover changes in the Soan catchment, using an image processing software. A rainfall-runoff model is used to assess hydrological behavior of the catchment. A good calibrated and validated model (hydrological) is applied for evaluation of potential impression of climate change on future water availability.

1.6 Benefits of Research Work

Assessment of footprints of climate change on water availability, for Soan catchment will be utilized by the stakeholders for:

i. Managing and conserving available water to tackle floods and droughts. (Authorities)
ii. Controlling and planning land use, land cover and urbanization trends. (Authorities)
iii. Developing policies for the best adaptation strategies. (Policy makers)

1.7 Organization of Thesis

Chapter 1 introduces the thesis topic, discuss background briefly and define objectives of study.

Chapter 2 presents the literature review. A brief literature review was done about hydrological model, climate change, land use changes.

Chapter 3 presents detailed methodology and It explains the location map of study area and salient features of the Soan basin and hydro-meteorological stations in the catchment. It also describes methodology, tools and techniques adapted during the research.

Chapter 4 discuss results

Chapter 5 give conclusions and recommendations

CHAPTER 2

LITERATURE REVIEW

2.1 General

In this chapter brief introduction about methods, tools and techniques has been presented. Literature on few of the previous and homogeneous studies have also been discussed.

2.2 Erdas Imagine Software

Erdas Imagine is defined by data observation network as an image processing software package that allows users to process both geospatial and other imagery as well as vector data. Hyperspectral imagery and LIDAR are also handled by Erdas through different sensors. For modeling 3D viewing module (Virtual GIS) and a vector module is also provided by Erdas.

2.3 Image Classification

Image classification is defined as the phenomenon of sorting pixels in to a finite number of individual classes or categories of data based on their data file values**.** A pixel is assigned to a certain class only if pixel fulfills a certain criterion. Also this classification of pixels in to classes is known as image segmentation. (Guide, 2010, Inc, 1997)

Following are the two methods to categorize pixels in to various categories:

i. Supervised
ii. Unsupervised

2.3.1 Supervised Classification

Unsupervised training is more computer-automated. This type of training relies on data for definition of classes. When less information is known about the data then this method is used. After classification, it is the analyst’s job to give meaning to the resulting classes. (Jensen, 1996).

Another name for unsupervised training is clustering because when the image data is plotted in feature space then it is based on natural grouping of pixels. These groups can afterwards be merged, disregarded, manipulated or used as the basis of signature according to the specific parameters. (Guide, 2010).

2.3.2 Unsupervised Classification

This type of training is closely controlled by the analyst. In this phenomenon, you pick pixels that define patterns or land cover features that you can comprehend, or that can be identified from other source like aerial photos, maps or ground truth. Before classification it is essential for the knowledge of data and classes. The similar characteristic pixels can be identified by instructing the computer system to identify different patterns. In case of accurate classification, the determined classes shows the categories within the data that you originally identified. (Guide, 2010).

2.4 HEC-GeoHMS

The US Army Corp of Engineers developed HEC-GeoHMS. It is used as a geospatial hydrology toolkit for hydrologists and engineers with limited GIS experience. The program allows users to visualize spatial information, document watershed characteristics, performs spatial analyst, delineate sub basin and streams, construct inputs to hydrologic models, and assist with report preparation. The hydrologic input can be used directly with HEC-HMS. This hydrologic input is swiftly created by working with HEC-GeoHMS through its tools, interface, menus, button and context sensitive online help. (Doan, 2000) **.**

2.5 Hydrological Model – HEC-HMS

The hydrologic engineering center has developed the computer program of HEC-HMS which is the "US Army Corps of Engineers Hydrologic Modeling System." The program simulates precipitation runoff and routing processes, both controlled and natural. For rainfall-runoff routing simulation HEC-HMS provides precipitation specification option which can describe an historic precipitation events, frequency based hypothetical precipitation event or event that represents the upper limit of precipitation possible at given location, loss model, direct runoff model, hydrologic routing models, distributed runoff model, continues soil moisture accounting model (USACE, 2000).

The model of HEC-HMS can be applied to different geographical areas that contain small urban or natural basin runoff and large river catchment flood hydrology and water supply. The things that need to be defined when developing any HMS model are Basin Model, Metrological model and Control Specifications. A basin model configures a physical description of watersheds or basins and rivers. To replicate a run off mechanism, hydrologic elements are connected in dendritic network. The hydrologic elements that are available are reach, sub basin, reservoir, source, diversion and sink. Metrological model carries out metrological data analysis and it includes evapotranspiration and precipitation. Control specification controls the time duration of simulation, which comprises computation time step, starting time and date and ending time and date. (Fleming, 2004)

2.6 General Circulation Models (GCM's)

The most advanced tool presently available for simulating the reaction of the global climate to expanding greenhouse concentrations are numerical models (General Circulation Models or GCM's) showing physical mechanisms is ocean, cryosphere, atmosphere and land surface.(IPCC, 2013)

2.7 Representative Concentration Pathways (RCPs)

RCPs are defined as "Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover" (Moss et al., 2008). There are four RCP's that are generated from Integrated Assessment Models picked from the published literature. In AR5 Chapter 11 to 14, these RCP's are availed in "Fifth IPCC Assessment" as a base for climate forecasting and projection. Four RCP's scenarios are as under:

2.7.1 RCP2.6

In this pathway, the radioactive forcing peaks at nearly 3 W m^{-2} prior to 2100 and then decreases (the corresponding ECP assuming constant emissions after 2100).

2.7.2 RCP4.5 and RCP6.0

Two intermediate stabilization pathways in which radiative forcing is stabilized at approximately 4.5 W m^{-2} and 6.0 W m^{-2} after 2100 (the corresponding ECPs presume constant concentrations after 2150).

2.7.3 RCP8.5

It is high pathway for which radiative forcing exceeds 8.5 W m^{-2} by 2100 and continues to ascent for some length of time (the corresponding ECP presume constant emissions after 2100 and constant concentrations after 2250).

2.8 Bias Correction

Bias correction approach is simply defined as the correction of daily projected raw GCM output. The method used is the difference in mean and variability between GCM and observation in a reference period. The output that we normally get from GCM or RCM outputs are biased. Before using these outputs for regional impact studies there is a requirement to correct these outputs (Ahmed et al., 2013).

Following are the models we can use for Bias correction:

- Linear Scaling (LS)
- Local Intensity Scaling (LOCI)
- Power transformation (PT)
- Variance scaling (VARI)
- Distribution Mapping (DM)
- Quantile Mapping (QM)
- Delta Change Approach etc. (Fang, Yang, Chen & Zammit, 2015)

2.9 Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF)

According to WMO (Organization, 2009), Probable Maximum Precipitation (PMP) is defined as “the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of year, with no allowance made for long-term climatic trends”. Probable Maximum Flood (PMF) depends on Probable Maximum Precipitation (PMP). The various techniques used for the calculation of PMP & PMF are as under.

2.9.1 Physical Methods

i. Maximization & transposition of actual storms (based on calculation of storm efficiency with the help of maximum observed rainfall & amount of precipitable water. Difficult owing to non-availability of data

ii. Local method (local storm maximization / local model)

iii. Combination Method

2.9.2 Statistical Methods – (Normally used for PMP Calculation)

The Hershfield technique is widely used to estimate the PMP which is based on general frequency equation modified by (Chow et al., 1988) as;

$$PMP = X_n + (K_m \times S_n)$$

Where X_n and S_n are the mean and standard deviation of maximum series of N years respectively, and K_m is frequency factor. The empirically derived coefficient K_m is calculated by using formula given as:

$$K_m = (X_m - X_{n-1}) / S_{n-1}$$

Where X_m is the highest value of the annual series, X_{n-1} is mean of the annual series excluding the highest value and S_{n-1} is the standard deviation of annual series excluding the highest value.

2.10 Previous Studies

(Koike et al., 2015) The model that was used to examine intra-basin river run off is physical based water and Energy Budget-based Distributed hydrological Model (WEB-DHM).This model was also used investigate in detail the possible impacts of climate change on hydrology in Soan River Basin, Pakistan, which is poorly gauged and semi-arid basin (PGB).The performance of the model was checked in the form of soil mixture and river discharge. The soil Land data Assimilation system developed by the University of Tokyo (LDAS-UT) authenticated WEB-DHM simulated surface soil mixture. WEB-DHM was derived with bias corrected precipitation and other parameters from four Atmosphere-Ocean General Circulation Models (AOGCMs). In the future, the 20 year data analysis of simulated daily discharge for past (1981-2000) and future (2045-2065) indicate that there is more likely a chance that the flooding trend will increase. Still, there is a probable chance that drought will also increase in future.

(Butt et al., 2015) In their study, ERDAS imagine was used and supervised classification maximum likelihood algorithm was applied. The purpose of its use was to detect land cover/ land use changes monitored in Simly watershed, Pakistan by using multispectral satellite data obtained from Landsat 5 and SPOT 5 for the years 1992 and 2012 respectively. The classification of the watershed was done in to five large land cover/use classes i-e Settlements, Agriculture, Vegetation, Bare soil/rock and water. As a result of land cover / land use and overlay maps produced in Arc GIS 10 designated an important change from Vegetation and Water cover to Agriculture, Bare soil/rock and Settlements cover, which shrank by 38.2% and 74.3% respectively. The watershed resources face a grave danger complete change in land cover/use. So for the contribution to the socioeconomic development of the area, proper management of watershed is needed. In the absence of proper management, these resources will be lost which will have a damaging effect on our lives as well as on environment.

(Shahid et al., 2017) The aim of the research is to access the comparative input of climate change and land use change to runoff change of the Soan River catchment. The tests that are used to discover trends and change point in hydroclimatic variables are Mann-Kendal and Pettit tests and period used were 1983-2012.The approaches that are applied to measure the impact of land use change and climate change on stream flow are abcd hydrological model and Budyko frame work. The results obtained from both the procedures are consistent and it clearly demonstrates that annual runoff has considerably decreased with a change point around 1997.The 68% detected change is because of decrease in precipitation and increase in potential evapotranspiration while the remaining detected change is due to land use change. During post-change period, the land use change obtained from Landsat demonstrates that agriculture has decreased in Soan basin which is a positive contribution of land use change to run off decrease. Foregoing in view, we have reached to the conclusion that above methods have performed well in measuring the comparative contribution of climate change and land use change to run off change.

(Bashir and Saeed Ahmad, 2017) Geospatial techniques, i.e., remote sensing and integrated GIS are used for effective land change study that is currently employed. Hybrid classification approach was applied using ERDAS Imagine 11 to detect changes in land cover dynamics using satellite imagery of Landsat 4, 5 TM, Landsat 7 ETM, and Landsat 8 OLI for the years of 1992, 2002, and 2015, respectively. The classification of study area was divided in to categories which is water body, vegetation, barren and urban area. By using ArcGIS 10.2 overlay maps, resultant maps, comparison maps were created which showed executional shrinkage of water body up to 58.81%, reduction in vegetation area 53.24%, and increase in urban and barren area to 49.04 and 137.32%, respectively. The survival of Soan river is under threat due to the important changes in land cover dynamics of river. So for saving Soan river, there is a strong need of appropriate management policies and development of land use inventory is needed.

(Yener et al., 2007) In this study, Yuvacık Basin, which is located in southeastern part of Marmara Region of Türkiye, is selected as the application basin with the drainage area of 257.86 km2 and hydrologic modeling studies are performed for the basin. For decision making support tool the calibrated model is used. The latest version of HEC-HMS is used for the purpose of studies of hydrological modeling. Modeling study comprises of two items out of which one is event-based hourly simulations and run off scenarios by using intensity-duration-frequency run off curves. Baseflow and infiltration loss guidelines of each sub basin are calibrated with hourly simulations as a result of studies of model application. For the prediction of run off hourly model parameters are employed in summer, spring and fall season. Runoffs that correspond to different return periods and probable maximum precipitation are predicted using intensity-duration-frequency data as input to frequency storm method of HEC-HMS. The run off values obtained as result of simulation can be employed for flood damage and flood control projection studies.

(Ahsan et al., 2016) This study analyzes climate change and associated hydrological effects as a result of altitudinal variability. For the prediction of climate change, variability analysis in precipitation, stream flow and temperature has been carried out. The outcomes of this study illustrate that maximum and mean temperature have warming trends and have increased with increased in elevation whereas minimum has the reverse situation. In areas of higher mountainous catchment, annual precipitation has more decreasing rate. The impact of altitudinal variability under changing climate yields that Annual stream flows in River Indus (at Khairabad and Kharmong, Alam), and Kabul (at Nowshera) Swat (at Kalam) have decreased whereas in River Hunza, Shigar, Astore Chitral, Shoyk. and Gilgit have increased. The established trends and fluctuation as a result of climate change has an effect on flows that should be taken in to the account by the water managers for better management of water in a water scarce country like Pakistan.

(Chen et al., 2009) combines an event-scale rainfall-runoff model and an empirical land use change model to quantify the impacts of potential land use change on the storm-runoff generation in the Xitiaoxi basin upstream of Taihu Lake watershed. The rainfall-runoff model in HEC-HMS is calibrated and authenticated for 7 storm events in study area. The result obtained from the model reveal good consistency between measured and simulated hydrograph at outlet of basin with its Nash–Sutcliff efficiency ranging from 75% to 95%. The CLUE-s model which is based on land use of 2002 is used to project two future land use scenarios for year 2050.Under the designed storm, HEC-HMS model is used for future land use scenarios. The results illustrate that future land use scenarios are forecasted to increase total run off as well as peak discharge and that the magnitude of increment relates to the expansion rate of built-up area.

(Rawat and Kumar, 2015) emphasizes the spatio-temporal dynamics of land cover / use of Hawalbagh block of district Almora, Uttarakhand, India. Landsat satellite imageries of two distinct time durations particularly over a period of 20 years, Landsat Thematic Mapper of 1990 and 2010 were obtained by Global Land cover Facility (GLCF) and earth explorer site and measure the changes in Hawalbagh block from 1990 to 2010. In ERDAS 9.3 software supervised classification methodology has been used by using maximum likelihood technique. The five various classes in which images of the study area were classified are agriculture, vegetation, built up, barren and water body. The conclusion shows that in last two decades, agriculture, barren land and water body have decreased by 1.52% (4.06 km2), 5.46% (14.59 km2) and 0.08% (0.22 km2) while vegetation and built up land have been increased by 3.51%

(9.39 km2) and 3.55% (9.48km2), respectively. The paper focuses the significance of digital change direction methods for nature and location of change of the Hawalbagh block.

The purpose of the (Karlsson et al., 2016) study was to make a model that would represent the combined effect of climate changes and land use on hydrology for an area of 486 km2 catchment in Denmark. The responsiveness of results is evaluated to the best choice of hydrological model. The three hydrological models namely NAM, SWAT and MIKE SHE, were established and calibrated by using identical mechanisms. Each model was forced with results from four climate models and four land use scenarios. The results obtained from these models displayed identical performance during calibration, the mean discharge response to climate change varied up to 30% and the difference were even higher for extreme events (1th and 99th percentile). It looks like that the land use change to cause minimal change in mean hydrological responses and it cause little variation between hydrological models. However, the change is significant for differences in hydrological model responses to land use where there is a case of extremes due to disparity in hydrological model structure and mechanism equations. The selection of climate model continues to be leading factor for low and high flows, mean discharge as well as hydraulic head at the end of century.

(Chu and Steinman, 2009) In their technical note, joint continuous and event hydrologic modeling with HEC-HMS is discussed and an application to the Mona Lake watershed in west Michigan is presented. The four precipitation events were chosen particularly with a purpose of calibrating / verifying the event model and determining the parameters of model. Which were then applied to the continuous hydrologic model. In HEC-HMS, the soil conservation service number and soil moisture accounting mechanism were used for simulating surface runoff in the continuous and event model respectively, and the relationship between two rainfall-runoff model was evaluated. These simulations gave hydrologic detail about variability, quantity and sources of run off in a watershed. The model output proposed that the fine-scale _5 min time step_ event hydrologic modeling, aided by comprehensive field data, is valuable for improving the coarse-scale _hourly time step continuous modeling by giving more accurate and well-calibrated parameters.

2.11 EFFICIENCY CRITERIA

2.11.1 Nash–Sutcliffe Coefficient (NS)

Nash–Sutcliffe Coefficient is used to “analyze the simulation power of hydrological models” (Krause et al., 2005). The governing equation is given below.

$$NS = 1 - \frac{\sum_{t=1}^{T}(Q_{ot} - Q_{mt})^2}{\sum_{t=1}^{T}\left(Q_{ot} - Q_{o}{}^{2}\right)}$$

Where, $Q_{\bar{o}}$ is the mean observed discharges, Q_m is modeled discharge at time t, Q_{ot} is observed discharge at time t.

*Nash–Sutcliffe efficiency can range from −∞ to 1.

2.11.2 Coefficient of Determination (R^2)

This is the “Square of correlation coefficient” (Krause et al., 2005). It is calculated as,

$$R^2 = \left(\frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{\{n\sum x^2 - (\sum x)^2\}\{n\sum y^2 - (\sum y)^2\}}}\right)^2$$

*Coefficient of determination value range from 0 to 1

2.11.3 Root Mean Squared Error (RMSE)

The RMSE is a “quadratic scoring rule which measures the average magnitude of the error” (Chai and Draxler, 2014). It is calculated as,

$$RMSE = \sqrt{\left(\frac{1}{n}\sum_{i=1}^{n}(model_i - observed_i)^2\right)}$$

* RMSE can range from 0 to ∞.

CHAPTER 3

DATA SET AND METHODOLOGY

3.1 General

The aim of this chapter is to discuss the procedures and methodologies implemented to achieve research objectives.

3.2 Study Area

Soan is a seasonal river of Punjab in Pothwar region (Jehanzeb, 2004), emerges from Murree mountains, passes from Rawalpindi, Fateh Jung, Pindi Ghab, Talagang, Mianwali and finally joins Indus River near Jand (Iqbal et al., 2004) has five major streams (Jehanzeb, 2004). In 1983 Simly dam was constructed on the Soan River to meet the water demands of capital city Islamabad. Korang, Khad, , Lei, Ling and Rumli are vital tributaries of the River Soan. Khad Nullah is the major feeder which emerges from Pabuchhian's springs and meet the Soan River near Chappar. Ling stream originates from many springs in Kotli Sattian and progress through Rawalpindi and Chakwal Districts, pair with Soan River near Sihala Mirzian. Nullah Korang is another feeding tributary of Soan River which is split into upper Korang (arises from spring of Bastaal and Charra Pani) and lower Korang over which Rawal dam is constructed, whereas Nullah Lei originates from Margallah Hills, moves through the cities of Islamabad and Rawalpindi, joins River Soan at Soan Camp (Malik et al., 2012). Approximate length of the Soan River is 274 km. Soan river basin located between 72.4°–73.5°E, 32.6°–33.9°N (Koike et al., 2015), is a semi-arid basin with an catchment area up to Dhok Pathan gauging station is 6475 sq. km (Jehanzeb, 2004).

Mean rainfall in the basin was 170mm, 178mm and 67mm during the monsoon months of July, August and September, respectively. November receives the lowest average rainfall of about 14mm. A much smaller winter rainfall peaks in February-March. Average monthly highest temperature varies between 35ºC and 41ºC while average monthly minimum temperature varies between 1ºC and 25ºC (Arshad Ashraf et al., 2016). The temperatures in the catchment also fall below zero at the higher altitudes in winter; while at lower altitudes temperatures of up to 47ºC are common in summer, particularly in the south of the basin. The Soan river catchment around Dhok Pathan experiences very warm summer, while the Murree hills in north have a freezing winter with snowfall. January is usually the coldest and June the hottest month in the year, with dust storms. The highest annual precipitation recorded in the Murree hills in the period 1960–1980 was 1,686 mm, with the maximum amount falling in July and August (Pakistan Meteorological Department, Historic Precipitation Database), this is a major source of moisture in the area (Abbasi et al., 2016).

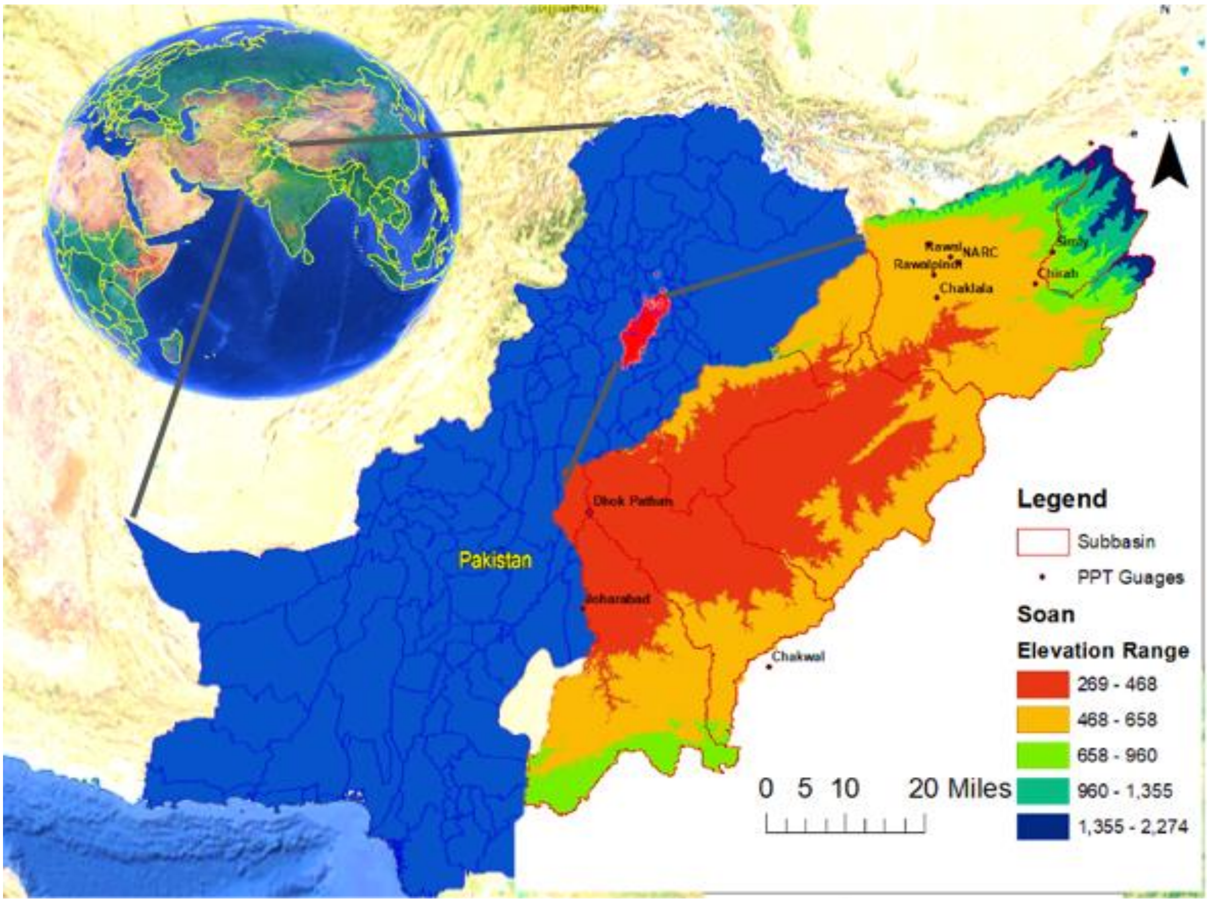


Figure 3-1 Soan River Catchment along with precipitation gauges and outlet

3.3 DISCRIPTION OF DATASETS:

3.3.1 Hydro-Climatic Data

3.3.1.1 Precipitation Data

Hydro-metrological data of this study was acquired from organizations like Water and Power Development Authority (WAPDA), Pakistan Metrological Department (PMD), Small Dams

Organization (SDO), Capital Development Authority (CDA), Surface Water Hydrology Project (SWHP) and National Agricultural Research Center, Islamabad (NARC). Daily precipitation data of six stations (Murree, Rawalpindi, Islamabad, Chakwal, Jouharabad and Kakul) was acquired from PMD, daily rainfall data for Rawal Dam, NARC, Khanpur Dam and Chirah rainfall gauging stations was acquired from SDO, NARC and SWHP and WAPDA respectively. Details of precipitation data used in study are shows in Table 3-1

Table 3-1: Precipitation Data

S. No	Type	Station	Acquired from	Location	Elevation (masl)	Period
1	Rainfall	Rawalpindi	PMD	33.648 73.085	508	1989-2013
2		Murre		33.916 73.383	2167	1983-2013
3		Islamabad		33.7 73.064	543	1985-2013
4		Chakwal		32.92 72.85	519	2006-2013
5		Chaklala		33.605 73.1	504	2007-2013
6		Jouharabad		32.5 72.433	187	2007-2013
7		Khanpur	WAPDA	33.802 72.929	88.41	2004-2013
8		Rawal	SDO	33.683 73.116	514	1984-2013
9		NARC	NARC	33.674 73.137	507	2000-2013
10		Simly	CDA	33.716 73.333	700	2004-2013
11		Chirah	SWHP	33.656 73.304	579	1986-2013

3.3.1.2 Stream Flow Data

Daily discharge data of Chahan, Chirah and Dhok Pathan gauging station is acquired from SWHP and WAPDA. Detail of flow data is shown in Table 3-2

Table 3-2: Stream Flow Data

S.No	Type	Station	Acquired from	Location	Elevation (masl)	Period
1	Stream Flow	Chahan	SWHP	33.425 72.867	391	2007 –2013 Daily
2		Chirah		33.656 73.304	579	
3		Dhok Pathan	WAPDA	33.125 72.034	269	

3.3.2 Remote Sensing Data

3.3.2.1 ASTER GDEM

30m x 30m resolution freely available Advanced Spaceborne Thermal Emission and Reflection Radiometer- Global Digital Elevation Map (ASTER-GDEM) is downloaded from USGS website "(http://gdex.cr.usgs.gov/gdex/)", Digital Elevation Model (DEM) is used for delineation of soan river catchment up to Dhok Pathan and different physical parameters were extracted like catchment area, slope, elevation etc. Soan catchment was then divided into seven subbasin based on outlet i.e. Chahan, Chirah and Dhok Pathan. Characteristics of Soan catchment are given in Table 3-3 and can be seen in Figure 3-2

Table 3-3: Characteristics of Soan Catchment

Elevation Range (m.a.s.l)	Mean Elevation (m.a.s.l)	Area (%)	Area (Km^2)
269 - 468	368.5	39	2543
468 - 658	563	45	2944
658 - 960	809	10	636
960 - 1355	1157.5	4	261
1355 - 2274	1814.5	2	131

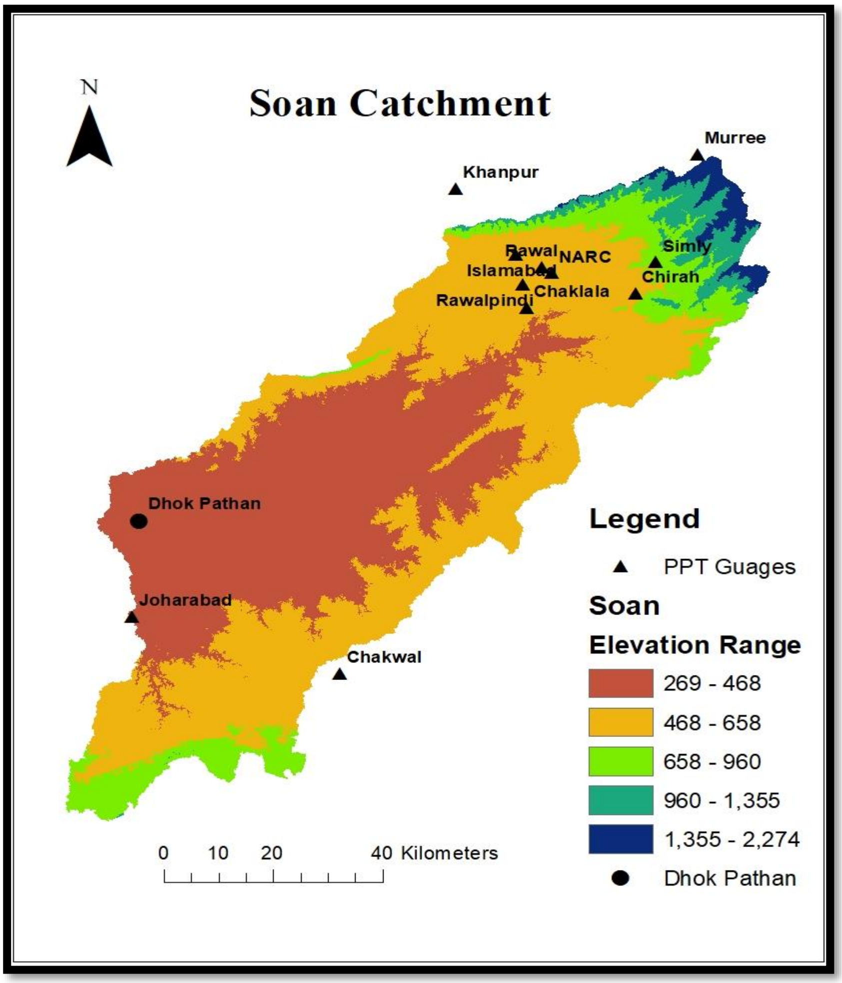


Figure 3-2 Soan Catchment along with Location of Climate Stations and Streamflow Gauging Station

3.3.2.2 Satellite Imagery

Satellite imagery of Landsat 07 for November, 2004 and Landsat 08 for June, 2014 was downloaded from freely available USGS website (https://earthexplorer.usgs.gov/) at 30×30 m resolution to extract land cover information shown in figure 3-3

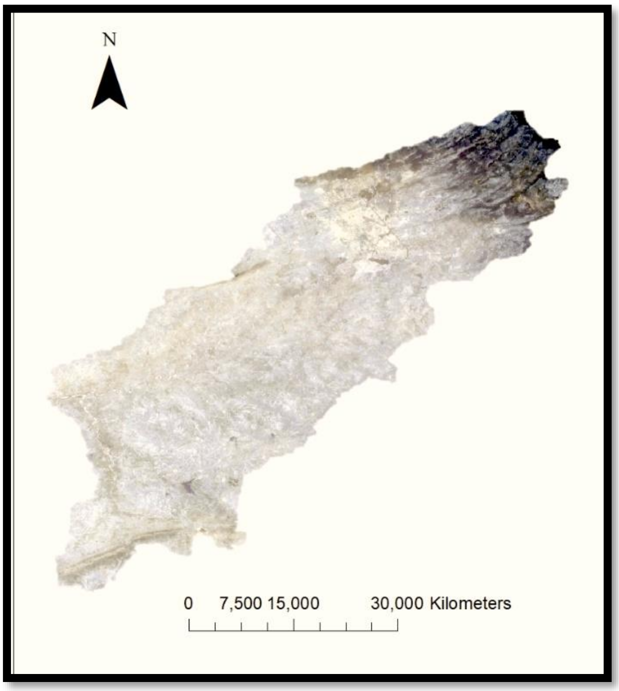


Figure 3-3: Landsat Image of Soan Catchment

3.3.2.3 Soil Data

FAO world soil dataset was extracted from freely available Food and Agriculture Organization (FAO) website (http://fao.org/home/en/) for the Soan catchment at 1:5,000,000 scale.

3.3.3 GCM Data

The datasets downscaled on the basis of Representative Concentration Pathways (RCPs) under HI–AWARE project, were obtained to study the projected changes in hydrological regime of Soan River catchment. (Lutz et al., 2016) scrutinized eight (8) GCM runs [inmcm4_r1i1p1, CMCC–CMS_r1i1p1, bcc–csm1–1_r1i1p1, CanESM2_r3i1p1 (RCP8.5); BNU–ESM_r1i1p1, inmcm4_r1i1p1, CMCC–CMS_r1i1p1, CSIRO–Mk3–6–0_r4i1p1 (RCP4.5)] from 163 GCM runs obtained from Coupled Model Intercomparison Project Phase 5 (CMIP5), for the IGB on the basis of extreme projections.. The projected precipitation dataset for General Circulation Models (GCMs) downscaled at 10x10 km grid size were obtained from HI–AWARE project. Himalayan Adaptation, Water and Resilience (HI–AWARE) project offers reference climate dataset (i.e. daily precipitation and mean air temperature) for the Indus, Ganges and Brahmaputra (IGB) River Basins. Further, detailed description of the aforementioned dataset used in current study is given by (Lutz et al., 2016)

3.4 Preliminary Analysis

3.4.1 Precipitation Analysis

The analysis on change in precipitation recorded on the climate stations present in Soan River catchment for the period 2007-2013 is shown in Figure 3-4. Precipitation over basin is calculated using Theisen polygon method for months from January to December so the current precipitation trend is representing whole catchment.

3.4.2 Stream Flow Analysis

The variation in observed streamflow on mean annual basis at Dhok Pathan station was analyzed to understand the hydrological behavior of Soan catchment. The data record is available for 14 years (2000–2013) duration. Maximum annual streamflow of 20,066 m^3/sec and minimum annual streamflow of 3808 m^3/sec was observed in 2010 and 2012, respectively shown in Figure 3-5 and mean annual streamflow of 10,731 m^3/sec was observed over 14–year (2000–2013) data record. Mean annual streamflow was also analyzed that shows slightly increasing trend.

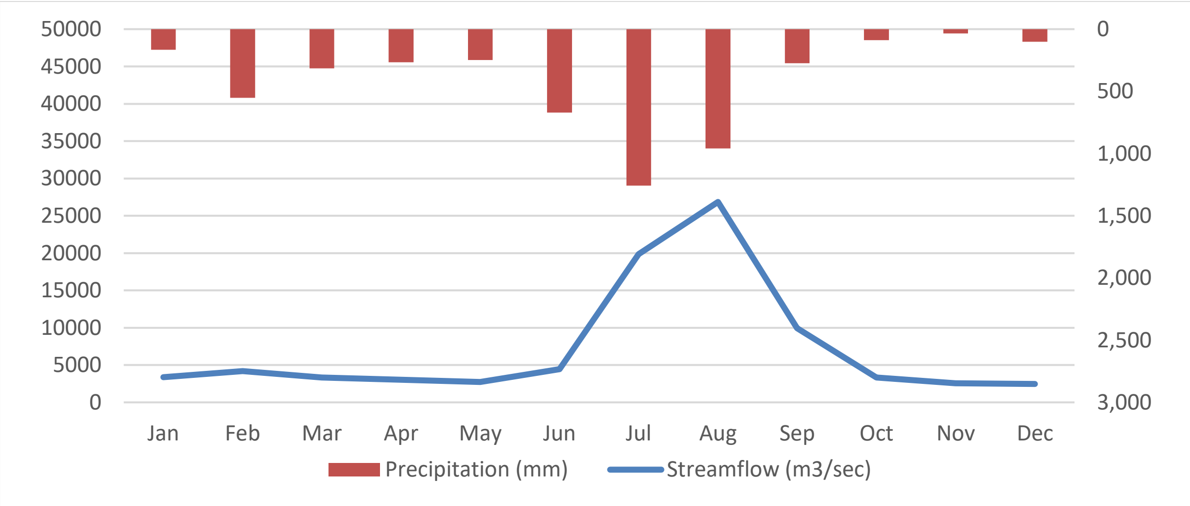


Figure 3-4: Time series data (precipitation and stream flow) 2007-2013

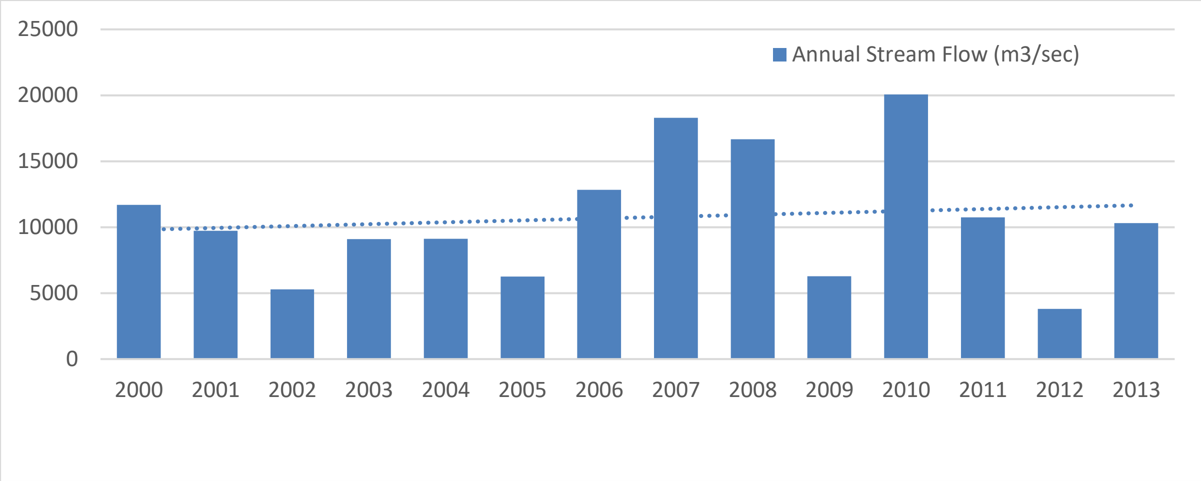


Figure 3-5: Stream flow at Dhok Pathan Station of Soan River

3.5 Methodology

Methodology adapted for the research is shown in figure 3-6 below and will be discussed further.

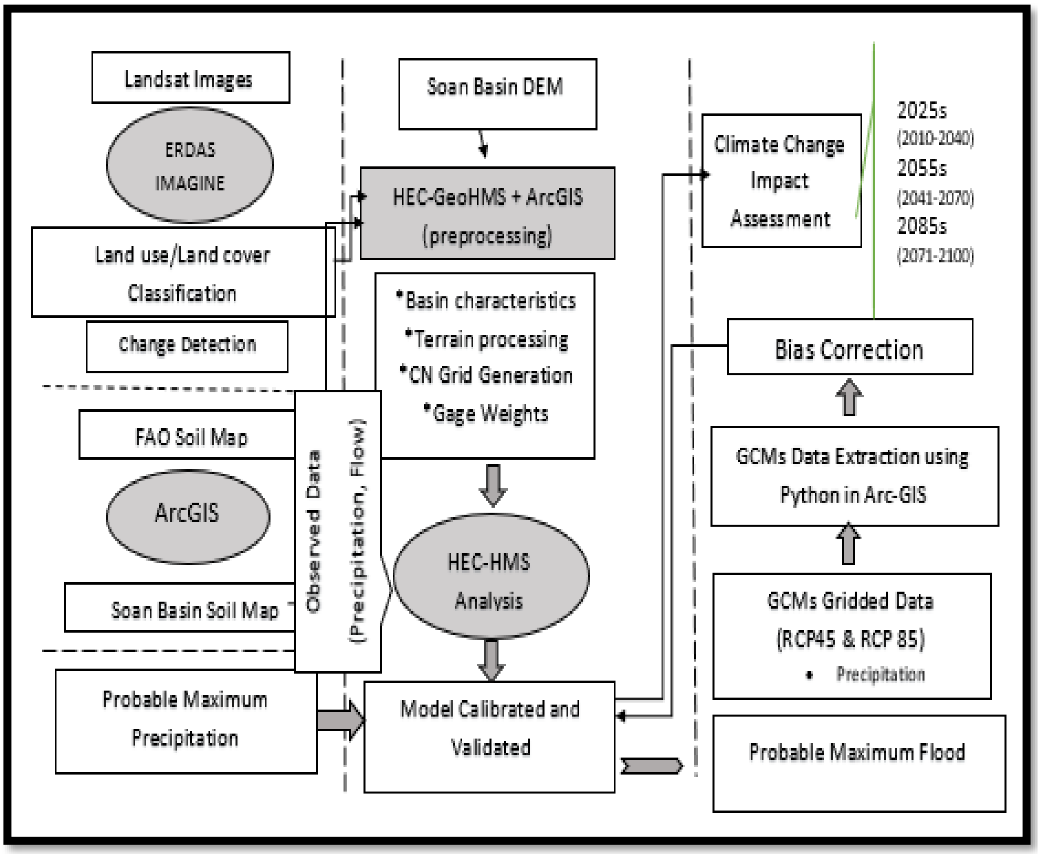


Figure 3-6 Schematic Diagram of Methodology Adapted

3.5.1 Land Use Analysis

Land cover pattern of soan river catchment was analyzed using ERDAS Imagine software. This phase involved extraction of soan Catchment imagery from the LANDSAT scene tile using ArcGIS. supervised classification technique was applied for carrying out land use classification. Soan Catchment was classified into five classes i.e. forest, built-up area, barren land, water bodies, vegetation. two imageries of different time frames (2004 & 2014) & same resolution were analyzed.

3.5.2 Preparation of Soil Map & Curve Number Grid

Soil classification map for Soan Catchment was extracted from FAO World Soil Map dataset. Based on the soil properties, soil was classified into two major hydrological groups B & C using the criteria defined by (Chow et al., 1988, NRCS, 2004). Lumped Curve number, land use data and soil groups were merged to generate composite curve number grid shown in Figure 3-7

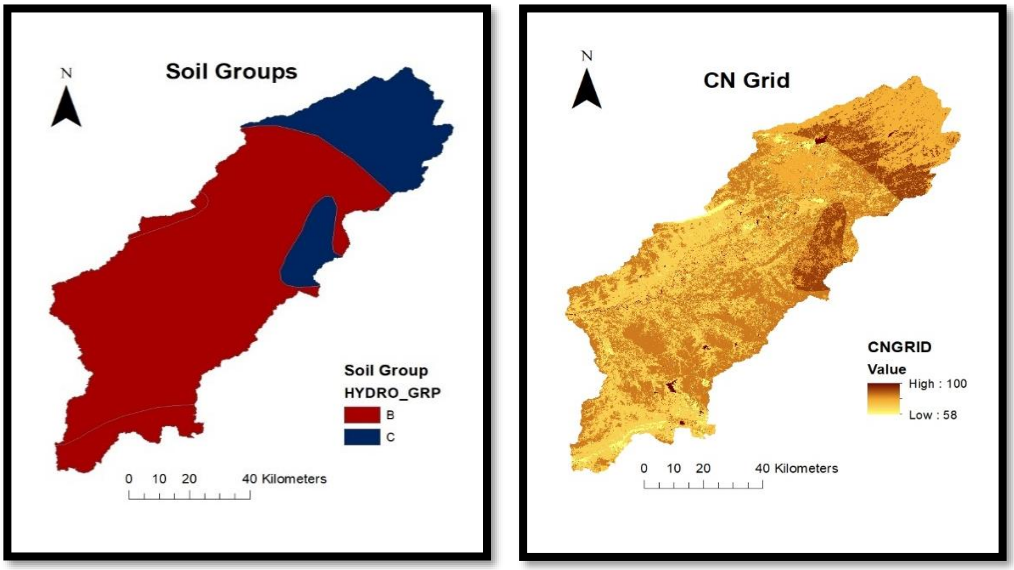


Figure 3-7: Hydrological Soil Groups and CN Grid of Soan Basin

3.5.3 Preparation of Spatial Precipitation Data

In order to convert point rainfall data to average rainfall over a basin, Thiessen Polygon or Weighted average rainfall values were computed shown in Table 3-4.

3.5.4 Hydrological Modeling System

The Hydrologic Modeling System (HEC-HMS) is planned to simulate the whole hydrologic procedures of dendritic watershed systems. Many hydrologic investigation procedures are included in software such as event infiltration, unit hydrographs, and hydrologic routing. necessary continuous simulation processes are also incorporated in HEC-HMS. Advanced capacities are also furnished for gridded runoff simulation using the linear quasi-distributed runoff transform (ModClark). It is a semi-distributed hydrological model which can be used for event based and continuous rainfall - runoff simulation. The land use information, hydrological soil groups and rainfall information with spatial and temporal variations is used as model input for rainfall – runoff simulation. It is planned to be suitable for a wide range of geographic areas for solving the extensive possible range of problems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff. Hydrographs produced by the program are used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, and systems operation(Fleming and Scharffenberg, 2018). HEC–HMS version 4.2.1 offers various methods to model loss, transfer, channel routing and baseflow shown in Table 3-5

3.5.4.1 Application of HEC-HMS:

Soan catchment was again divided into seven (7) subbasins which are as shown in Figure 3-8. Observed precipitation and discharge dataset were used as an important input. HEC–HMS comprises of four components such as basin model, meteorological model, time specifications and time series component**.**

Table 3-4: Guage Weights for Soan Catchment

Subbasin	Area(km^2)	Guage weights (%)	Climate Stations
1	1625	24 28 9 1 4 10 4 4 16	Chaklala Chirah Islamabad Khanpur Murree NARC Rawalpindi Rawal Simly
2	1482.7	54 46	Chaklala Chakwal
3	508.73	39 55 6	Chaklala Chakwal Khanpur
4	1069.9	100	Chakwal
5	1146	68 32	Chakwal Johrabad
6	271.83	58 11 8 23	Chaklala Islamabad Khanpur Rawalpindi
7	333.26	4 34 61	Chirah Murree Simly

3.5.5 Model Calibration and validation:

In this study various methods to model loss, transfer, channel routing and baseflow with different combination were used for hydrological modeling to select best fit combination shown in table 3-6. The daily stream flows were simulated at Dhok Pathan by using Deficit and constant (loss), SCS Unit Hydrograph (transfer), Lag Method (channel routing) and Constant Monthly” (baseflow) combination of methods. Model was calibrated for the period of four (4) years (2007-2010) and validated for (3) years (2011-2013).

Table 3-5: Methods available in HEC-HMS version 4.2.1

Loss Methods	Transform methods	Channel Routing Methods	Baseflow
Deficit and constant rate	Clark’s UH	Kinamatic wave	Bounded recession
Exponential	ModClark	Lag	Non-linear Boussinesq
Green and ampt	Kinamatic wave	Muskingum-cunge	Linear reservoir
Gridded green and ampt	SCS UH	Muskingum	Constant monthly
Initial and constant rate	User specified s-graph	Modified pulse	Recession
Gridded DC	Synders UH	Straddle-Stagger	
Gridded SMA	User Specified UH		
Gridded SCS CN			
Soil moisture			
SCS curve number			
Smith Parlang			
Accounting			

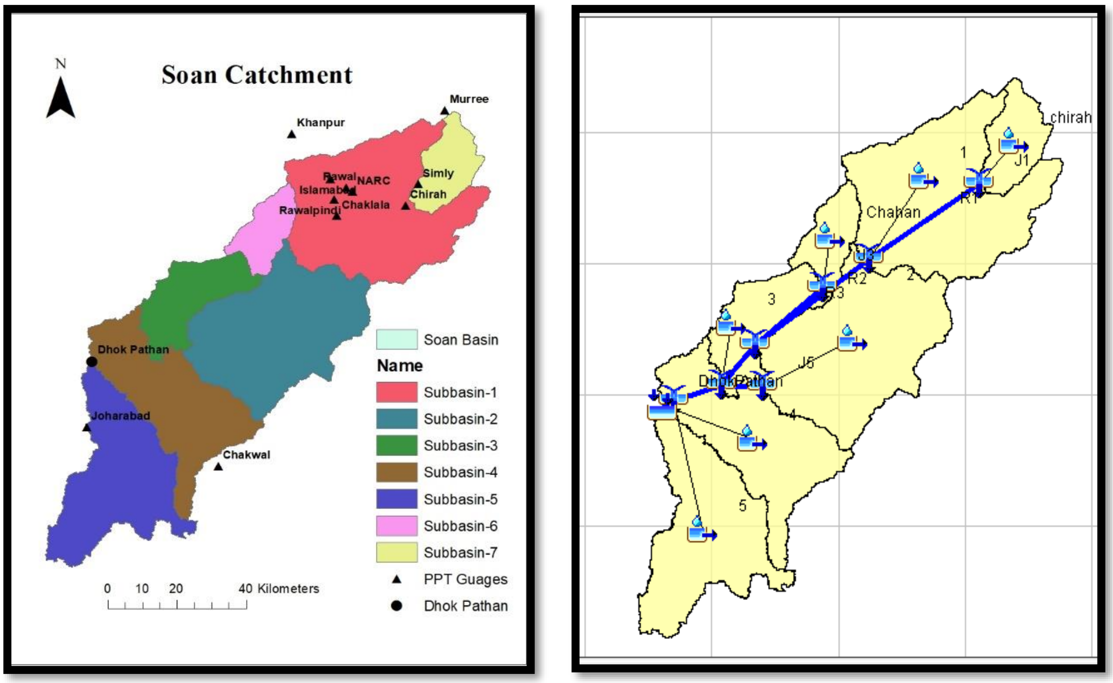


Figure 3-8: Seven subbasin of Soan Catchment used for HEC-HMS

Table 3-6: Methods used in HEC-HMS

Loss	**Transform**	**Routing**	**Baseflow**
Deficit and Constant method	SCS unit hydrograph	Lag Method	Constant Monthly
SCS curve number		Muskingum routing	
Initial and Constant			

Maximum storage, initial deficit, percent impervious, constant rate, lag time, time of concentration, optimized by trial and error approach. Base flow was calculated from the observed hydro–meteorological data. Initial values selected for HEC–HMS calibration of different parameter are given in Table 3-7

Table 3-7: Range of Parameter Values for Application of HEC–HMS

Parameter	Parameter value ranges for Soan Basin	Initial Values
Initial Deficit (mm)	5-12	Trial optimization
Max Storage (mm)	25-30	Trial optimization
Constant Rate (mm/hr)	1-1.8	Trial optimization
Impervious (%)	7-17	Trial optimization
Lag Time (hr)	4-13	Equation developed by US SCS for time of concentration
Routing Lag Time (hr)	1-9	Equation developed by US SCS for time of concentration

In order to assess goodness of fit among observed values and simulated results, various statistical parameters including coefficient of correlation (R^2), Relative root mean square error (RRMSE) & Nash-Sutcliffe Coefficient (E) were evaluated. Calibrated parameters were utilized as input values for model validation for three years. Model performance was again evaluated using above mentioned statistical parameters for assessment criteria of its validation.

3.5.6 Calculation of Probable Maximum Precipitation (PMP)

According to (WMO, 2009), Probable Maximum Precipitation (PMP) is defined as “the maximum depth of precipitation for a specified duration meteorologically possible for a specific watershed or a given storm area at a particular location at a particular time of year, with no allowance made for long-term climatic trends". Two main approaches are commonly in practice for calculation of PMP including physical approach and statistical approach (Casas *et al.*, 2011). Approach is based on meteorological analysis involves maximization and transposition of actual storms through storm classification and storm efficiency with the help of maximum observed rainfall & amount of precipitable water. This approach warrants availability of dew point temperature, dry and wet bulb temperature for calculation of precipitable water which is a major constraint. Statistical approach based on Hershfield technique is most widely used involving general frequency equation modified by (Chow et al., 1988) as;

$$PMP = X_n + (K_m \times S_n)$$

Where Sn and X_n is the standard deviation and average of maximum series of N years, and K_m is the frequency factor which is calculated by (Boota et al., 2015) by a formula

$$Km = (X_m - X_{n-1}) / S_{n-1}$$

Where X_m is equal to the highest value of annual series, X_{n-1} is the average of the annual series excluding the largest value and S_{n-1} is equal to Standard deviation of annual series excluding the highest value. (Ghahraman, 2008) shown that for number of stations within a catchment, highest value of Km to be taken as standard for all stations for calculation of PMP.

Values of Probable Maximum Precipitation (PMP) were used as input for validated HEC-HMS model to generate values of Probable Maximum Flood (PMF) at Dhok Pathan

Table 3-8: Details of Hi-AWARE GSMs

Type of GCMs	RCP 4.5	RCP 8.5	Climate Conditions
BNU-ESM_r1i1p1	x		cold, wet
inmcm4_r1i1p1	x		cold, dry
CMCC-CMS_r1i1p1	x		warm, dry
CSIRO-Mk3-6-0_r4i1p1	x		warm, wet
inmcm4_r1i1p1		x	cold, dry
CMCC-CMS_r1i1p1		x	warm, dry
bcc-csm1-1_r1i1p1		x	cold, wet
CanESM2_r3i1p1		x	warm, wet

3.5.7 Assessment of Climate Change Scenarios:

For future climate impact study, eight GCMs models downscaled at 10km × 10km grid size for Indus basin plains was selected from IGB climate dataset. Selection of eight GCMs is described in detail by (Lutz et al., 2016). Details of GCMs used in current study are shown in Table 3-8

3.5.8 Bias Correction of Climate Data Set

IGB daily precipitation dataset was extracted for eleven (11) stations at which climatic stations are physically located within the Soan River catchment, then the observed (baseline) and climatic dataset (climate station data) were compared with the IGB climatic dataset to observe uncertainties. Since, the large uncertainties were found in IGB climatic dataset in comparison with observed, therefore bias correction of IGB gridded climatic dataset were done on daily basis using the delta technique to derive corrected baseline (GCMs) climatic dataset for future decadal (2025s, 2055s, 2085s) climate. Where 2025s represent period from 2011-2040, 2055s represent time slice 2041-2070 and 2085s represent time slice 2071-2100. The climatic dataset was corrected by using correction factor driven from baseline (observed) and baseline (GCMs) dataset during base period (1983-2010).

3.5.9 RCPs Scenarios (RCP8.5 and RCP4.5)

The projected changes in climate variable (precipitation) both for RCP8.5 and RCP4.5 were assessed in comparison with the baseline (observed) and climatic dataset(precipitation). Subsequently, the corrected precipitation dataset was utilized as an input in hydrological model to project the potential daily stream flows in Soan River catchment, for RCP8.5 and RCP4.5 scenarios (bias corrected precipitation RCPs dataset).

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 General

This section deals with the interpretation of results obtained from research work.

4.2 Land use analysis

Land use maps of Simly catchment were prepared for year 2004 and 2014 using the ERDAS Imagine software. Soan River catchment was classified into five number of classes as, Barren Land, Built-up area, Forest, Vegetation and Water Bodies shown in Figure 4-1

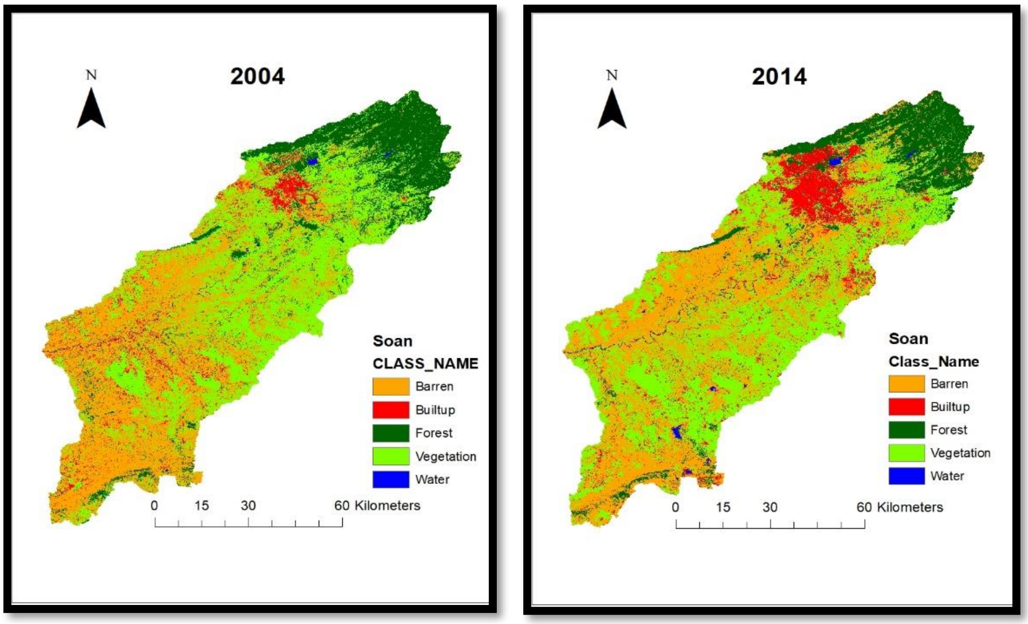


Figure 4-1: Land Cover Map of Soan Catchment

Maps reveal that the catchment is mostly covered with forest and bushes. Histograms presented in Figure 4-2 and Table 4-1 provide a better understanding to explore the changes experienced in the catchment from year 2004 to 2014. The major change is observed in forest covered area, which was 57% of total catchment area in 2004, decreased to 42.72% in 2014. Another decreasing trend is observed for bare land from 13% to 12%. Possibly land cover under these classes would be turned into built up, bushes or agricultural land. An outcome can be drawn from this set of information that catchment is undergoing sharp human activities. Built up land increased 13% which is considered as most influencing element to change the hydrological behavior (Schultz, 1995). It can be used as a hint to consider a population increase in the catchment (Zeug and Eckert, 2010). Vegetation (Agricultural land) increased by 0.13% and water body increased by 1.6%. respectively.

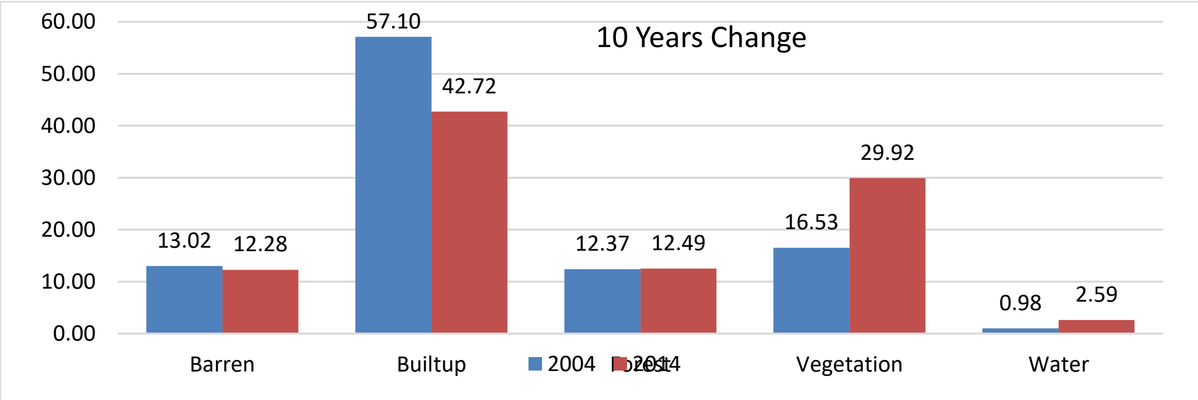


Figure 4-2: Percentage change in Land Cover

Table 4-1 Percentage Change in Land Cover Area from 2004 to 2014 for Soan Catchment

	2004		2014		Change (2004-2014)	
Land Cover	Percentage	Km^2	Percentage	Km^2	Percentage	Km^2
Barren	13	843	12	795	-1	-48
Builtup	17	1070	30	1937	13	867
Forest	57	3697	43	2766	-14	-931
Vegetation	12	801	12	809	0	8
Water	1	63	3	167	2	104

4.3 Hydrological Analysis

4.3.1 Model Calibration and Validation

For the study, it is found that a set of methods consist of deficit and constant loss method for losses calculation, constant monthly base flow, SCS unit hydrograph for transformation, and routing method for river routing, provide best results as compare to any other set of combination. Statistical performance during model calibration and validation lies in acceptable range. For calibration Nash-Sutcliff coefficient is found as 0.59 and for validation periods 0.528. Root mean square error (RMSE) results into 73.1 and 73.8 for calibration and validation period respectively. For calibration and validation period the coefficient of determination is 0.6774 and 0.7247. The parametric values of finally selected methods for hydrological assessment of Soan Catchment are presented in Table 4-1. Model was calibrated for a period of four years (2007-2010) and validated for three years (2011-2013).

The hydrographs of rainfall-runoff analysis generated by HEC-HMS along with observed discharge values measured at Dhok Pathan gauge station during calibration and validation of model are shown in figure 4-3 and 4-4 respectively.

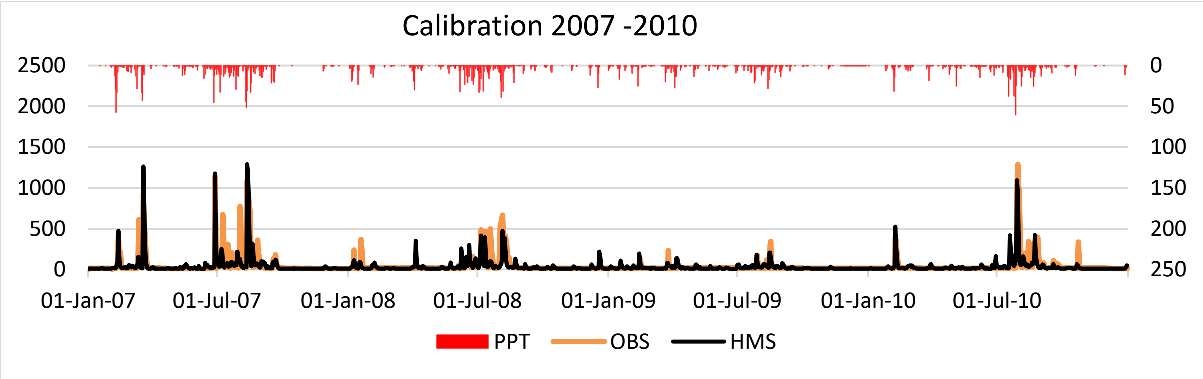


Figure 4-3: Hydrological Model Calibration

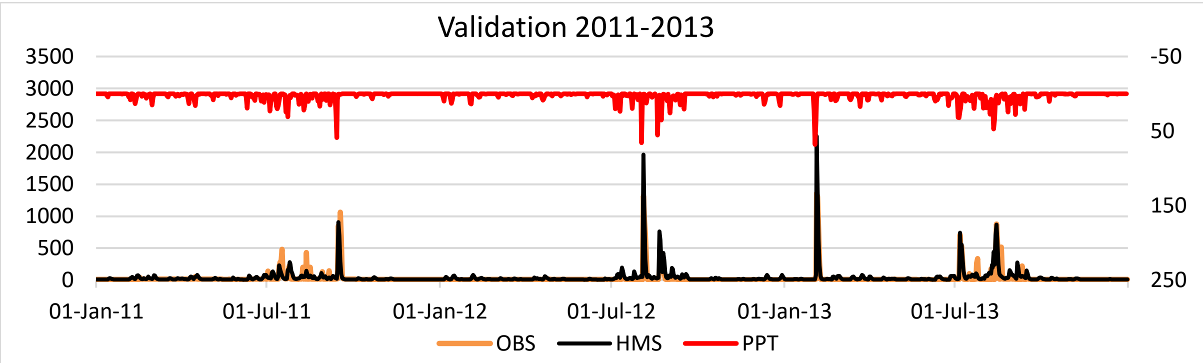


Figure 4-4: Hydrological Model Validation

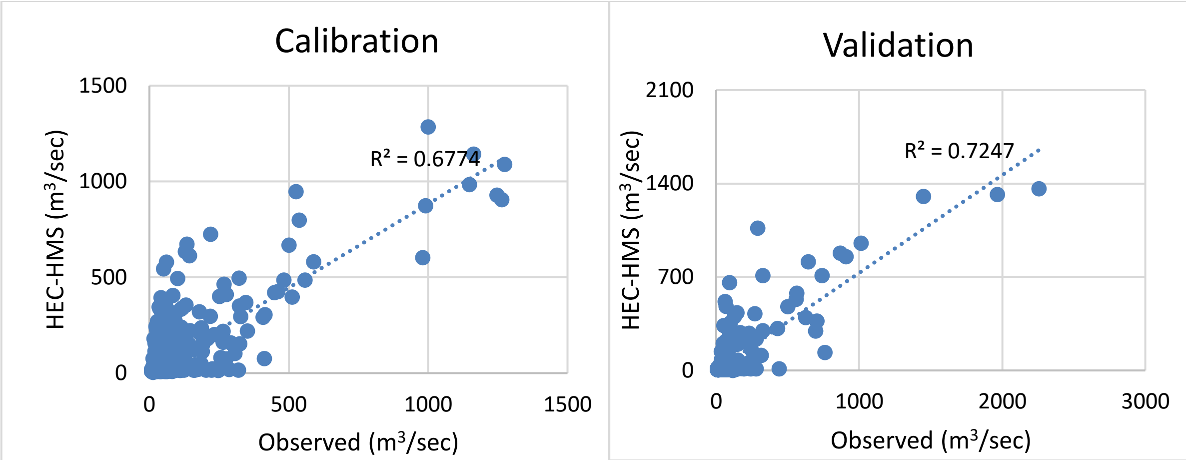


Figure 4-5 Scattering of Observed & HEC-HMS Simulated flow

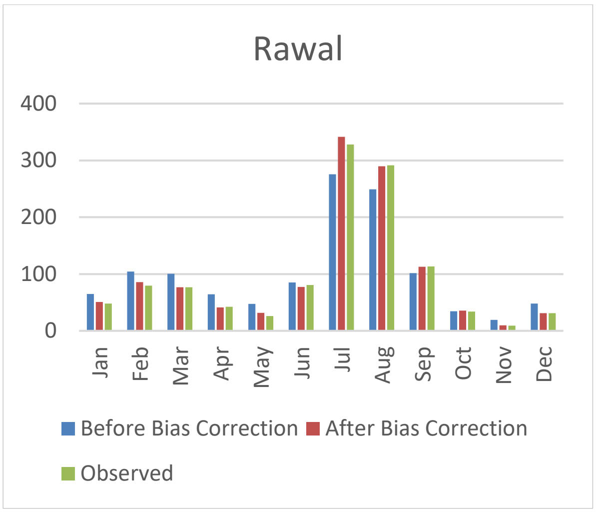
Table 4-2: Calibrated Subbasin Wise Parametric Values for HEC–HMS Model

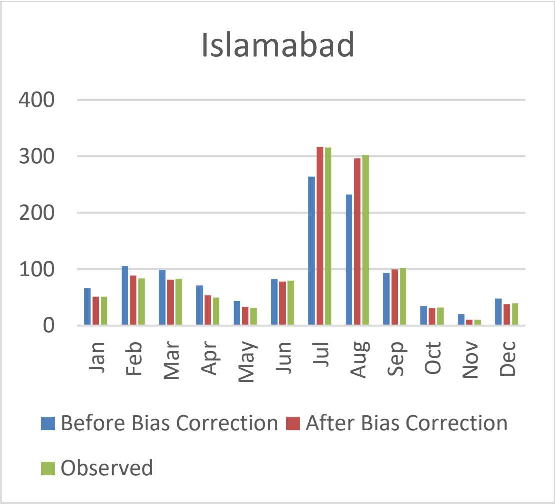
	Subbasin						
	1	2	3	4	5	6	7
Initial Deficit (mm)	13	5	5	5	5	6	15
Max Storage (mm)	30	30	30	30	30	25	25
Constant Rate (mm/hr)	1.2	1	0.9	1.3	1.2	1.2	1.7
Impervious (%)	15	8	9	8	7	10	17
Lag Time (min)	587.79	660.87	524.36	751.84	669.59	284	240
River Routing							
	R1	R2	R3	R4	R5	R6	R7
Lag Time (min)	520	405	410	220	175	225	80

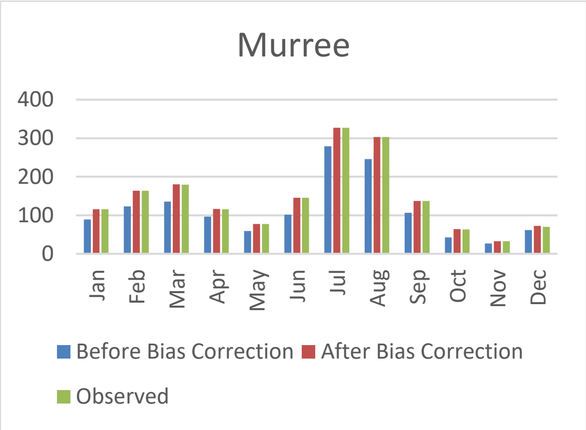
4.4 Climate Change Impact Assessment

4.4.1 Bias Correction

Comparison of reference data before and after bias correction with observed data, for eleven stations was done. After bias correction, monthly average bar charts match very well with observed data. The correction factor derived from baseline data was applied at future projected data of each individual GCM. Comparison of mean monthly observed and bias corrected precipitation is shown in figure 4-6


Rawal
400
300
200
100
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Before Bias Correction
After Bias Correction
Observed


Islamabad
400
300
200
100
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Before Bias Correction
After Bias Correction
Observed


Murree
400
300
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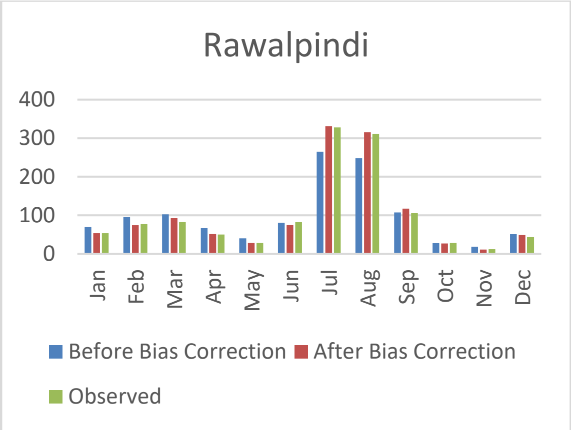
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Before Bias Correction
After Bias Correction
Observed


Rawalpindi
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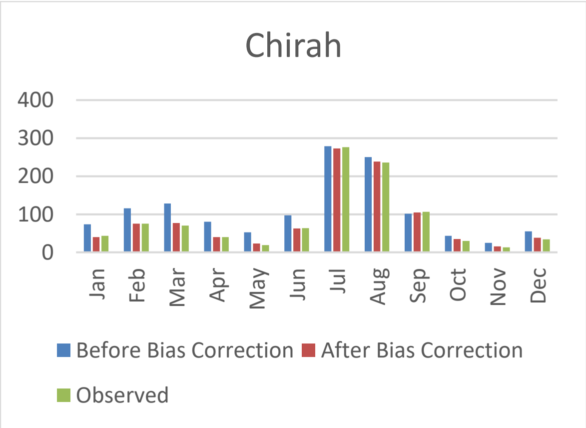
Observed


Chirah
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Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Before Bias Correction
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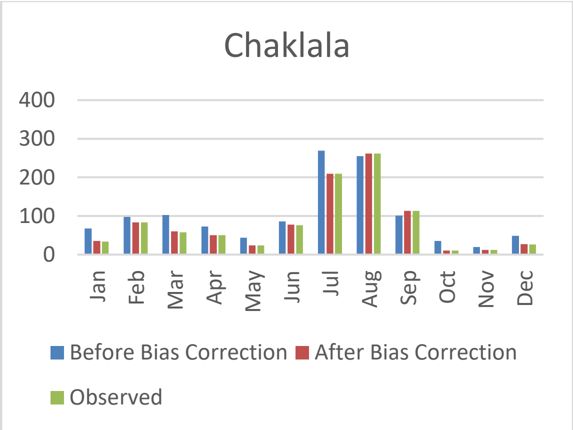
Observed


Chaklala
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Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Before Bias Correction
After Bias Correction
Observed

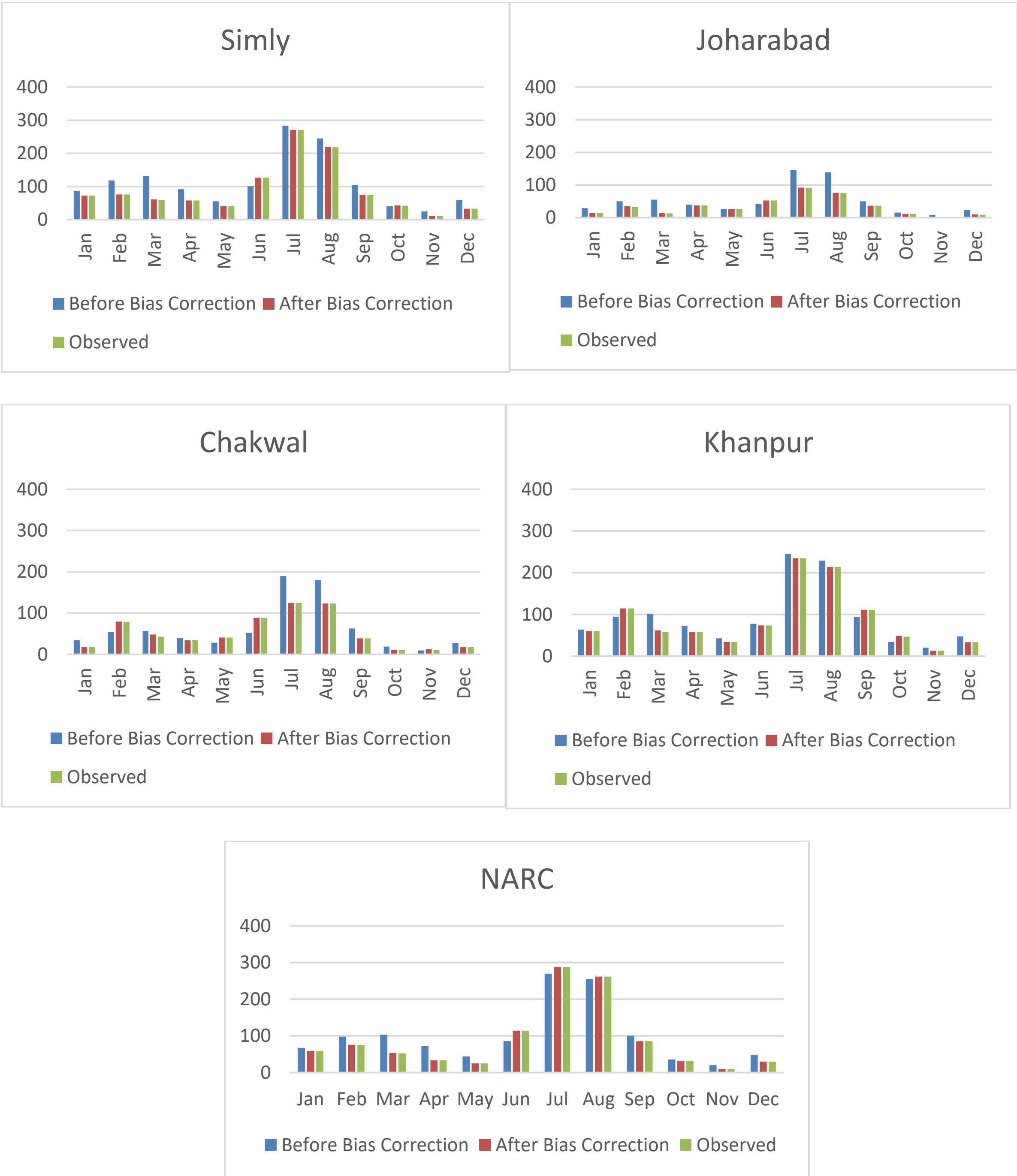

Figure 4-6: Comparison of mean monthly observed and bias corrected precipitation from 1983-2010.

4.4.2 Change in Precipitation under RCP4.5 and RCP8.5

At Murree station the future rainfall trend for RCP8.5 & RCP4.5 is like baseline in a manner that there two precipitation peak, one post winter and other is post summer. For particular climate change scenario, under RCP4.5, the climate model BNU-ESM_RCP45_rlilp1 predicts higher precipitation for month of April for all time slices and also for month of September in time slices 2025s & 2085s. For 2025s, CSIRO-Mk3-6-0_rcp45_r4ilp1 behavior is noticeable that projected precipitation for July and August is high in comparison to other models and baseline. Under RCP8.5, for same climate station, the outputs of bcc-csm1-1_rcp85_r1i1p1 predicts higher precipitation for monsoon period for all time slices, especially for 2055s, the projected precipitation for month of September is considerably at higher side. in similar way, in comparison to CanESM2_rcp85_r3i1p_1 and CMCC_CMS_rcp85_r1i1p1, the climate model inmcm4_rcp85_r1i1p1predicts higher precipitation for month of July & August for time slices 2055s and 2085s.

At Islamabad climate station, the projected behavior for winter and post winter precipitation is much similar to baseline under RCP4.5 and RCP8.5 climate change scenario. Under RCP4.5, climate model BNU-ESM_RCP45_rlilp1 projects increase in precipitation for months of July to September. Also, CSIRO-Mk3-6-0_rcp45_r4ilp1 predicts an increase in precipitation for month of August for all time slices. Under RCP8.5 climate change scenario, bcc_csm1-1_rcp85 predicts an increase in precipitation for monsoon. Meanwhile, inmcm4_rcp85_r1i1p1 predicts increase in monsoon precipitation for period of 2055s & 2085s except 2025s.

At Rawal climate station, under RCP4.5 future precipitation change scenario, the climate models inmcm4_rcp45_R1i1p1 and CMCC_CMS_rcp45_r1i1p1 predicts a considerable increase in precipitation comparing to baseline for month of July in 2025s rather than any other model. The climate model CSIRO-Mk3_60_rcp45 outputs presents a gradual increase in monsoon precipitation from period of 2025s to 2085s. Under RCP8.5, the behavior of climate model bcc_csm1_1_rcp85_r1i1p1 predicts increase in precipitation for all times especially month of September. whereas, inmcm4_rcp85 which predicts decrease in precipitation for time slice of 2025s, presents a considerable increase in precipitation for months of July till end of century and this increase is much higher for period of 2085s.

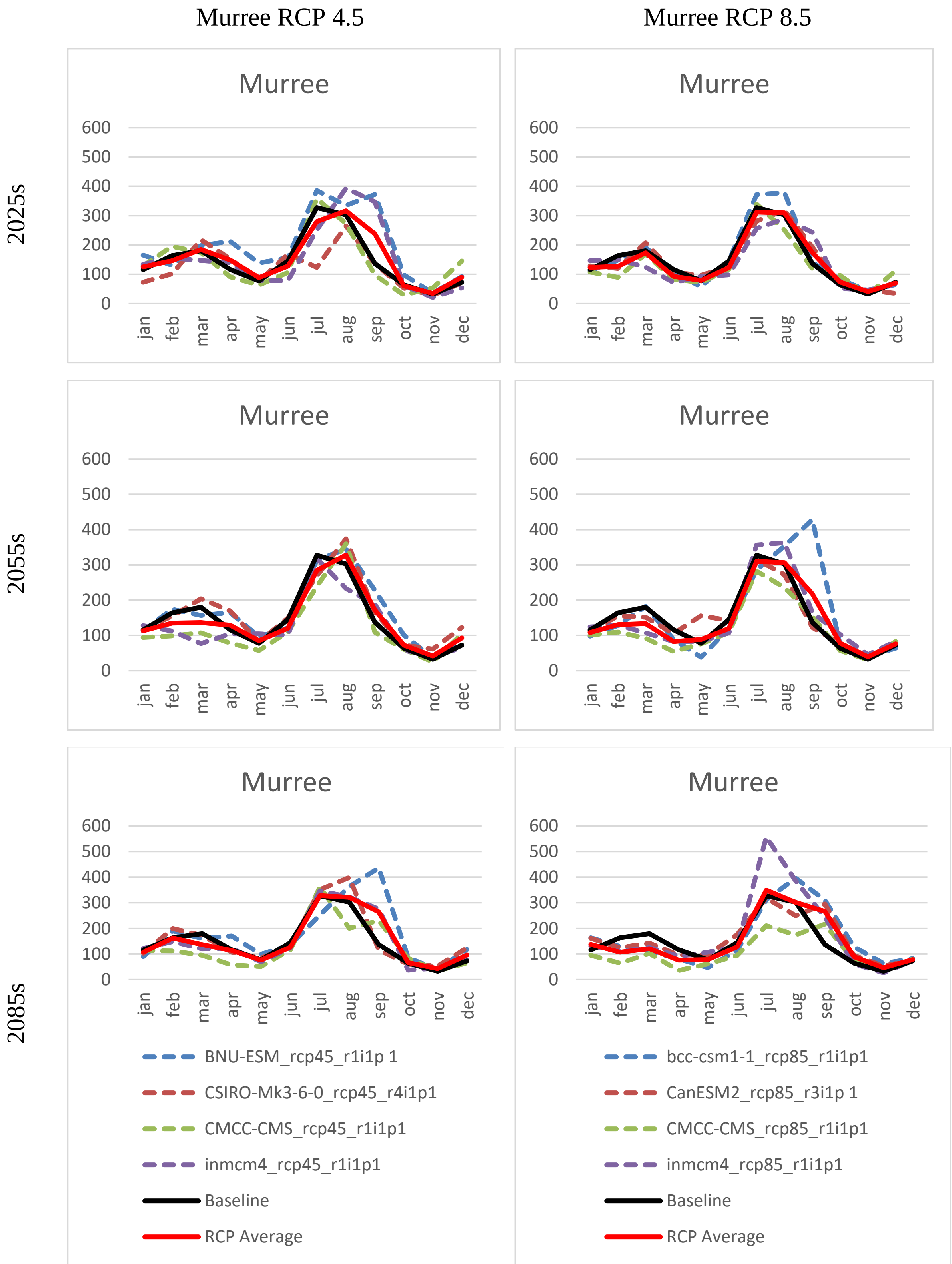

Figure 4-7: Projected changes in Precipitation at Murree Station

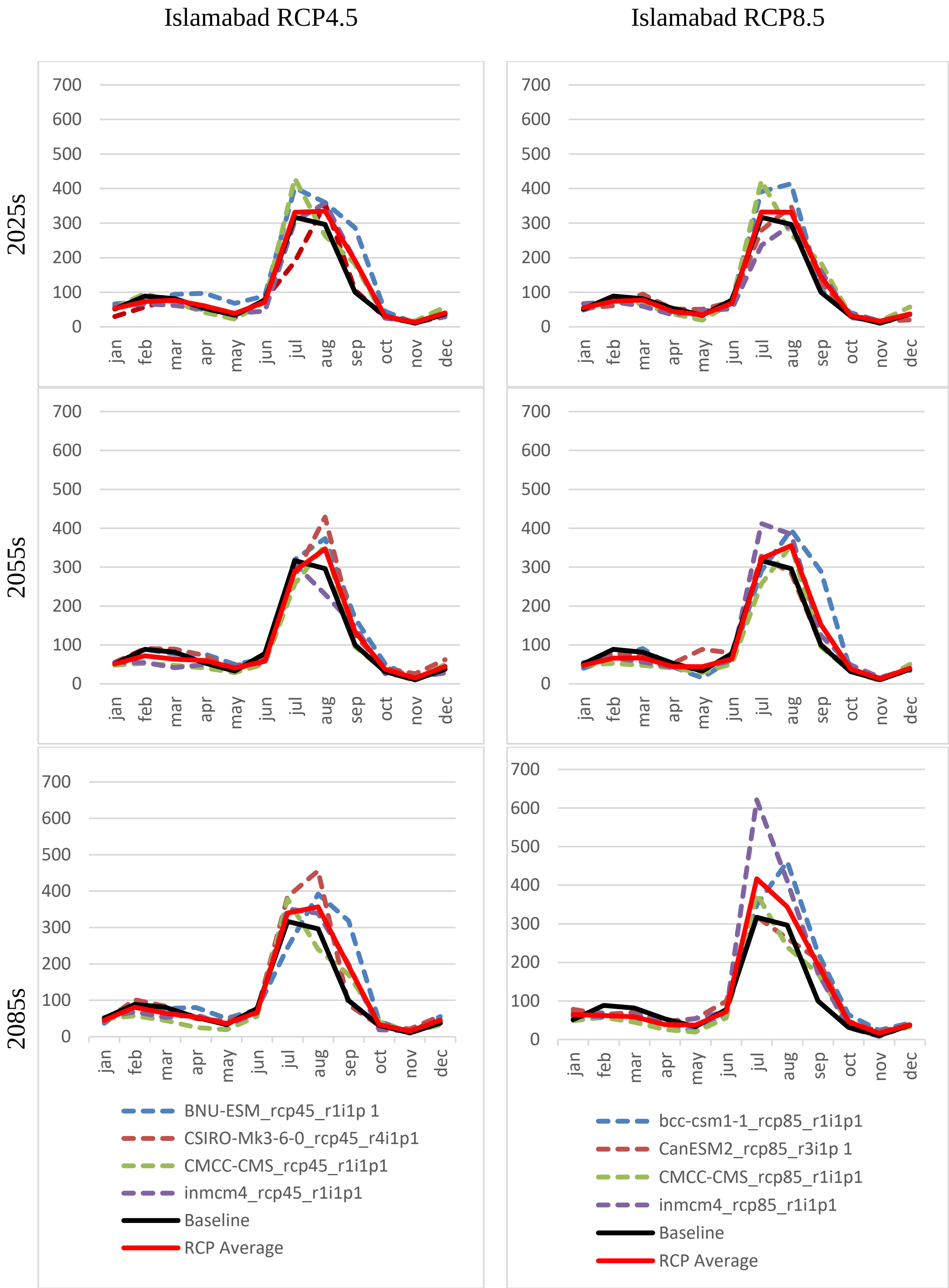

Figure 4-8: Projected changes in Precipitation at Islamabad Station

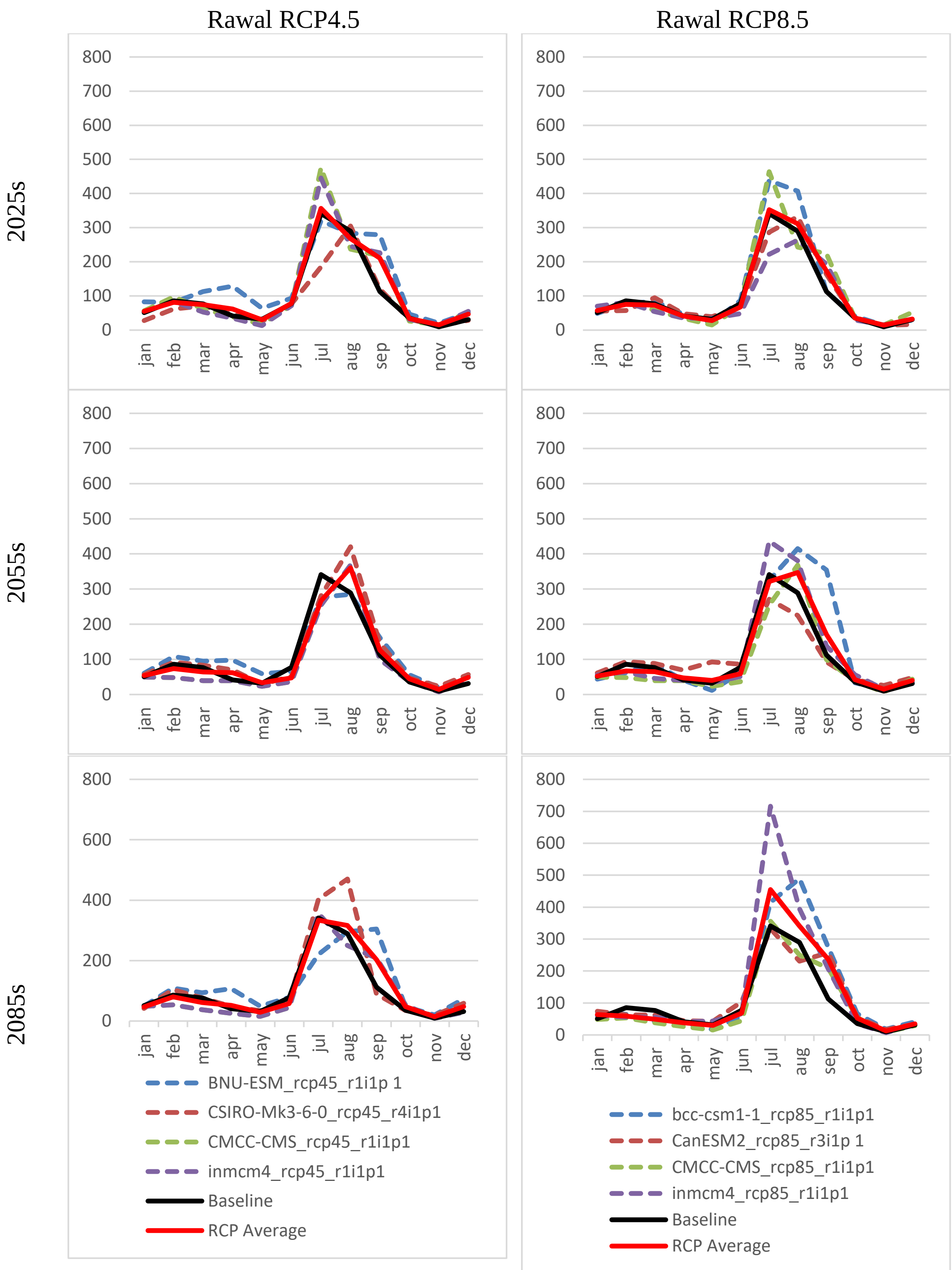

Figure 4-9: Projected changes in Precipitation at Rawal Station

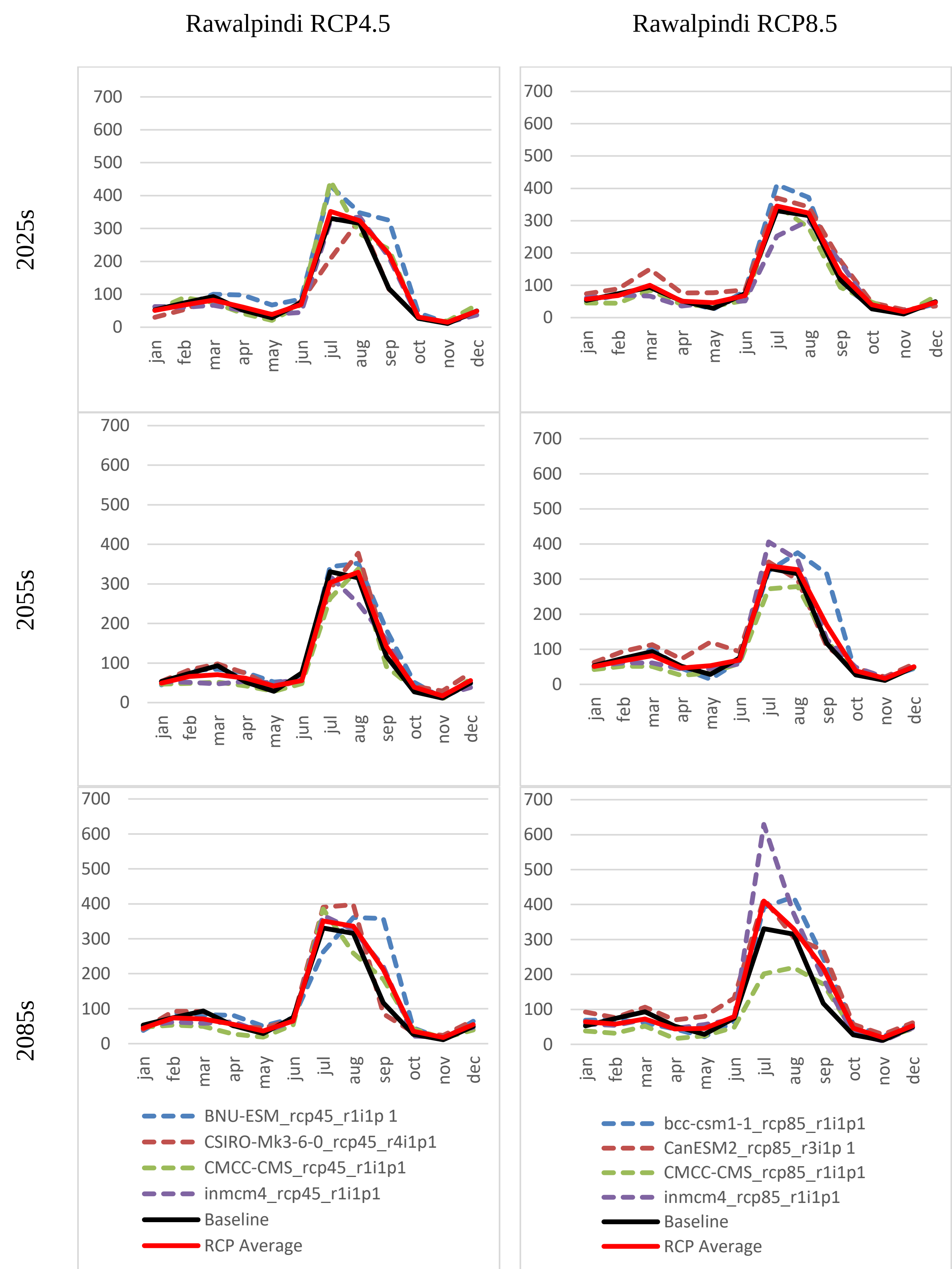

Figure4-10: Projected changes in Precipitation at Rawalpindi Station

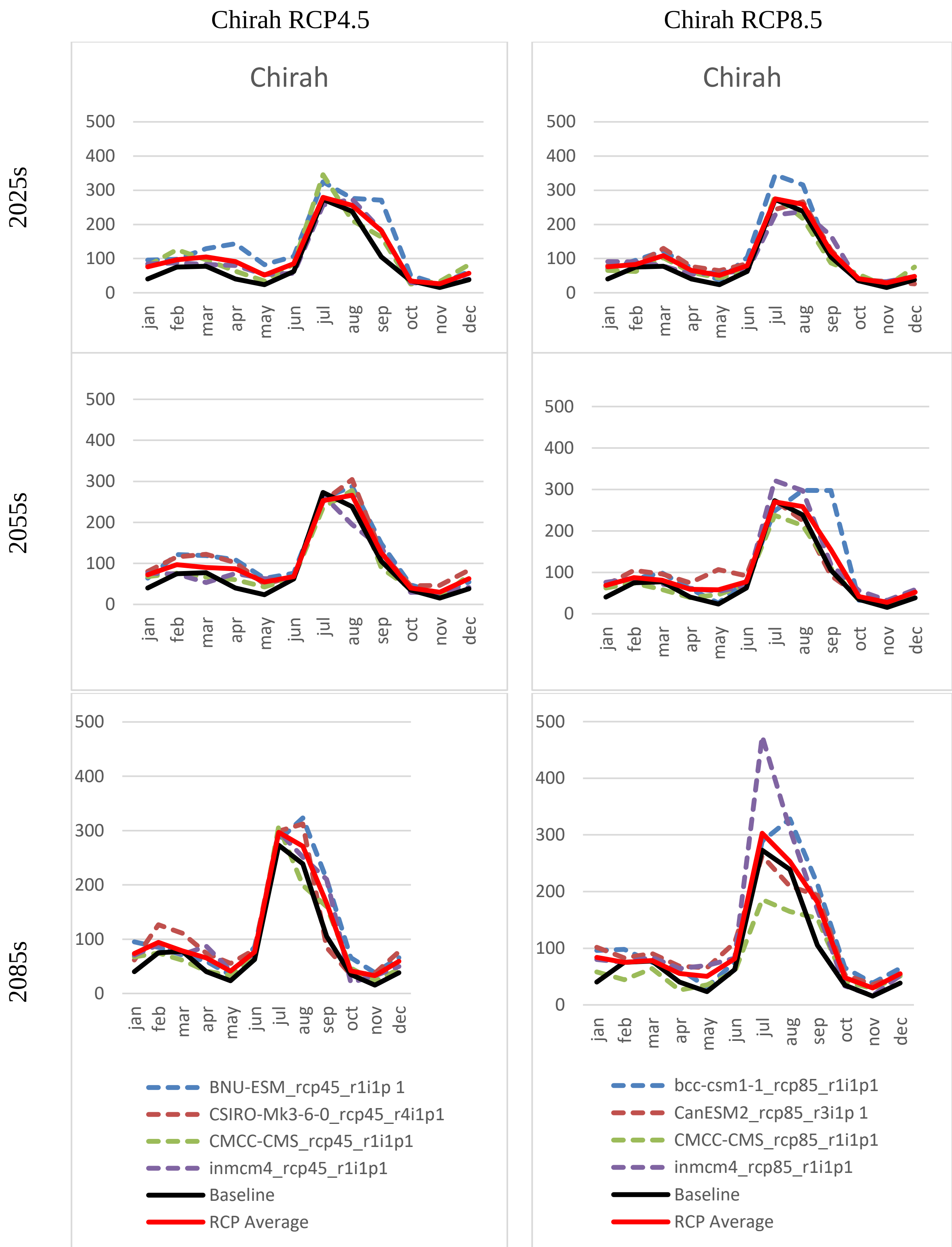

Figure4-11: Projected changes in Precipitation at Chirah Station

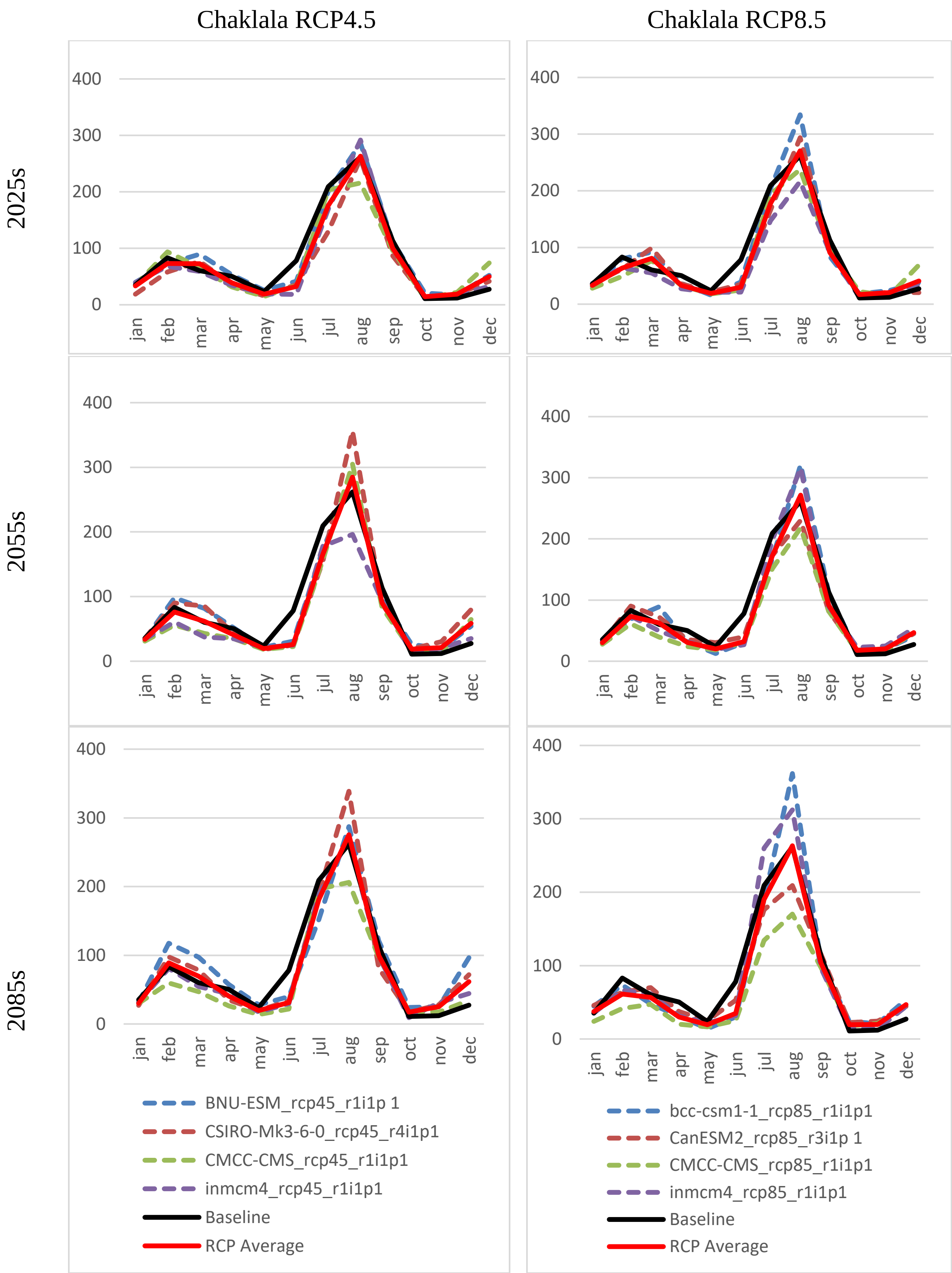

Figure 4-12: Projected changes in Precipitation at Chaklala Station

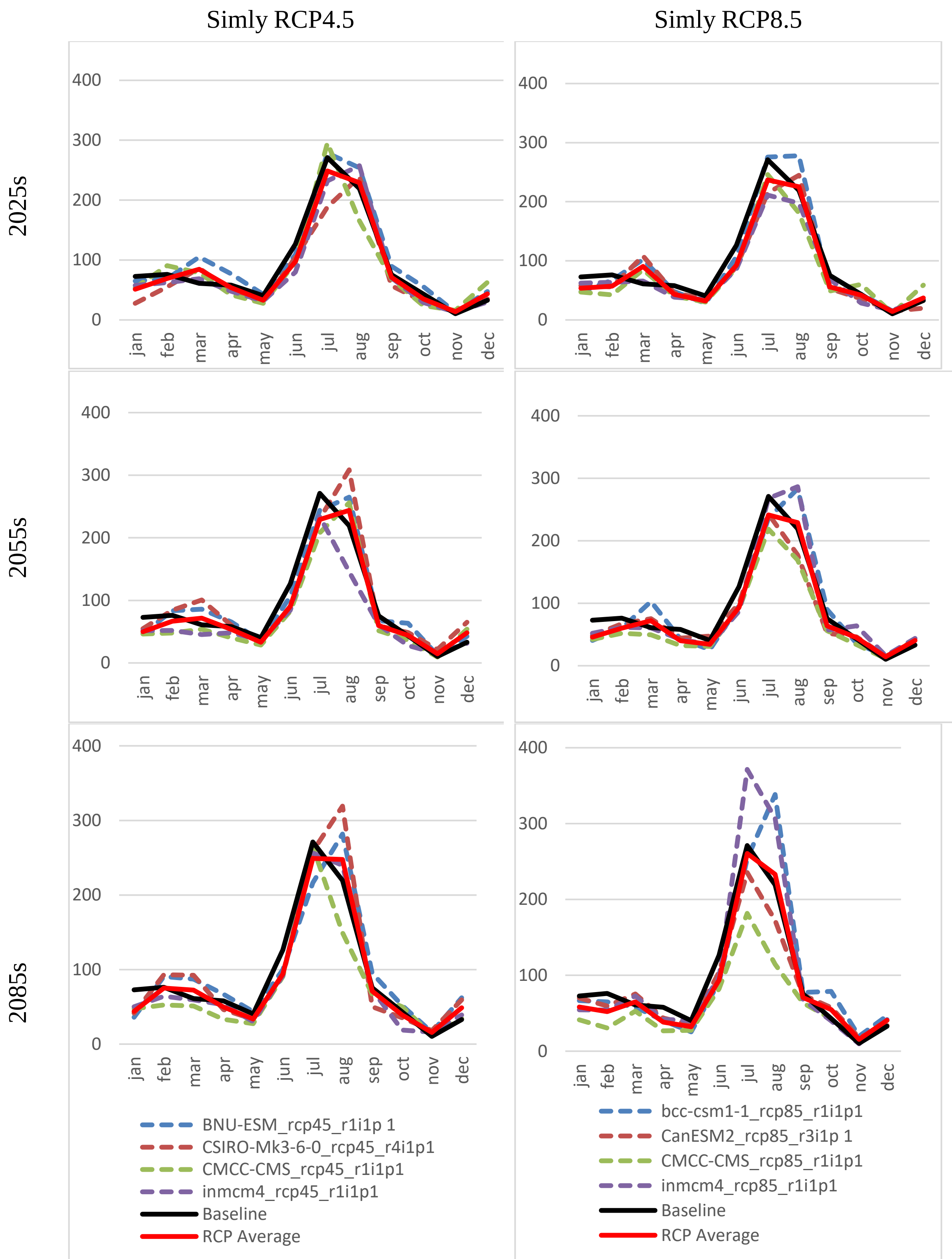

Figure 4-13: Projected changes in Precipitation at Simly Station

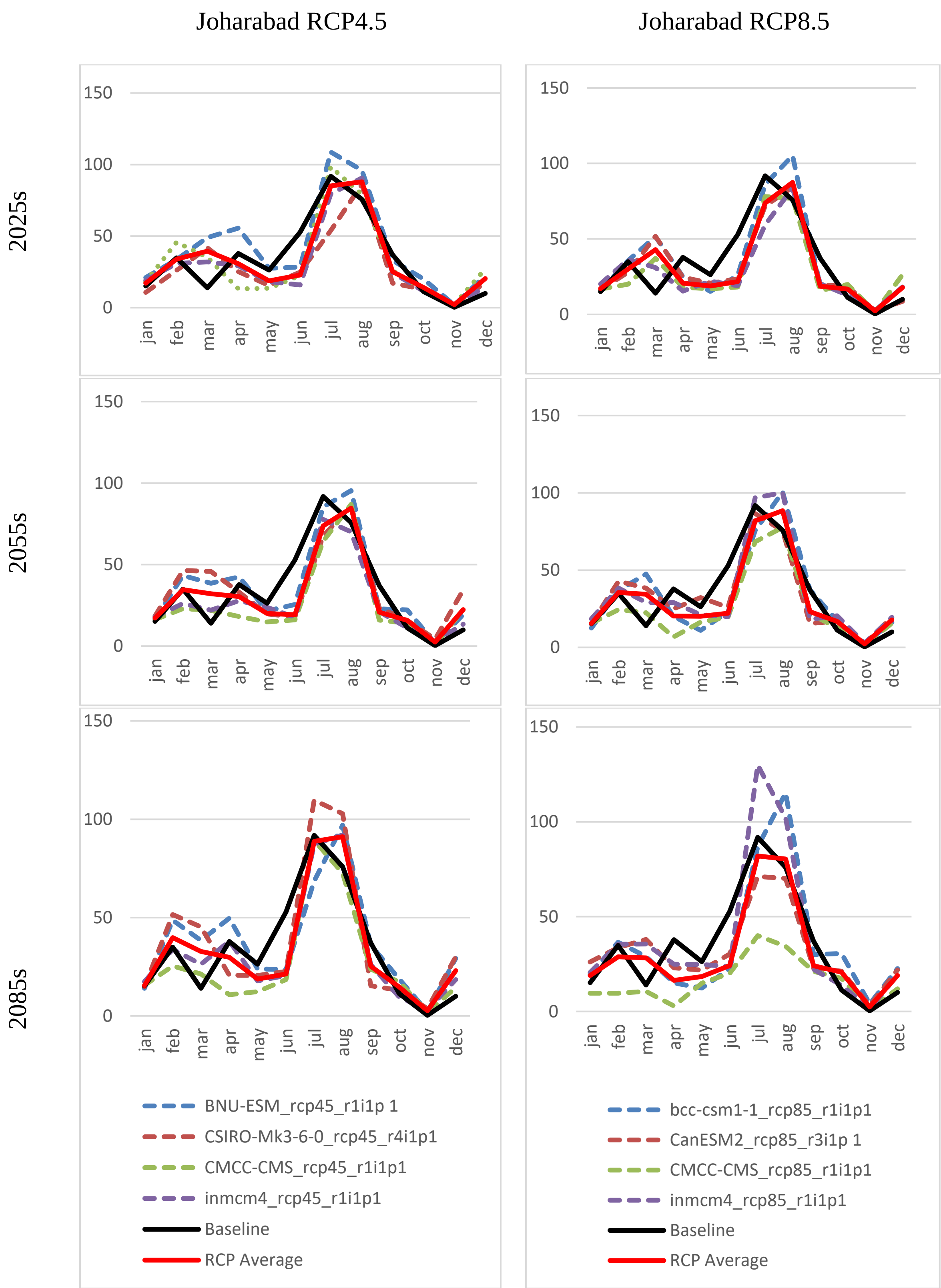

Figure 4-14: Projected changes in Precipitation at Joharabad Station

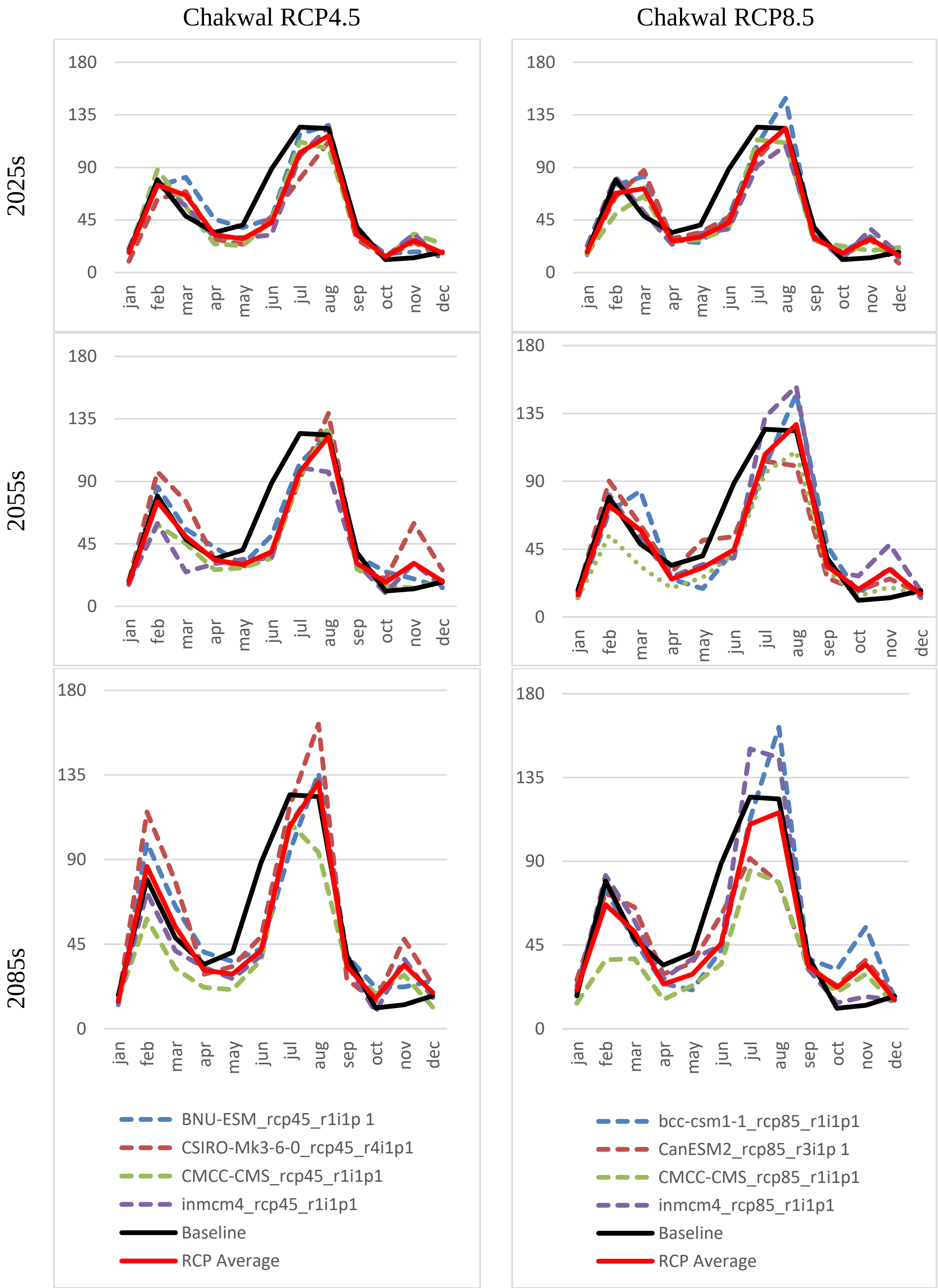

Figure 4-15: Projected changes in Precipitation at Chakwal Station

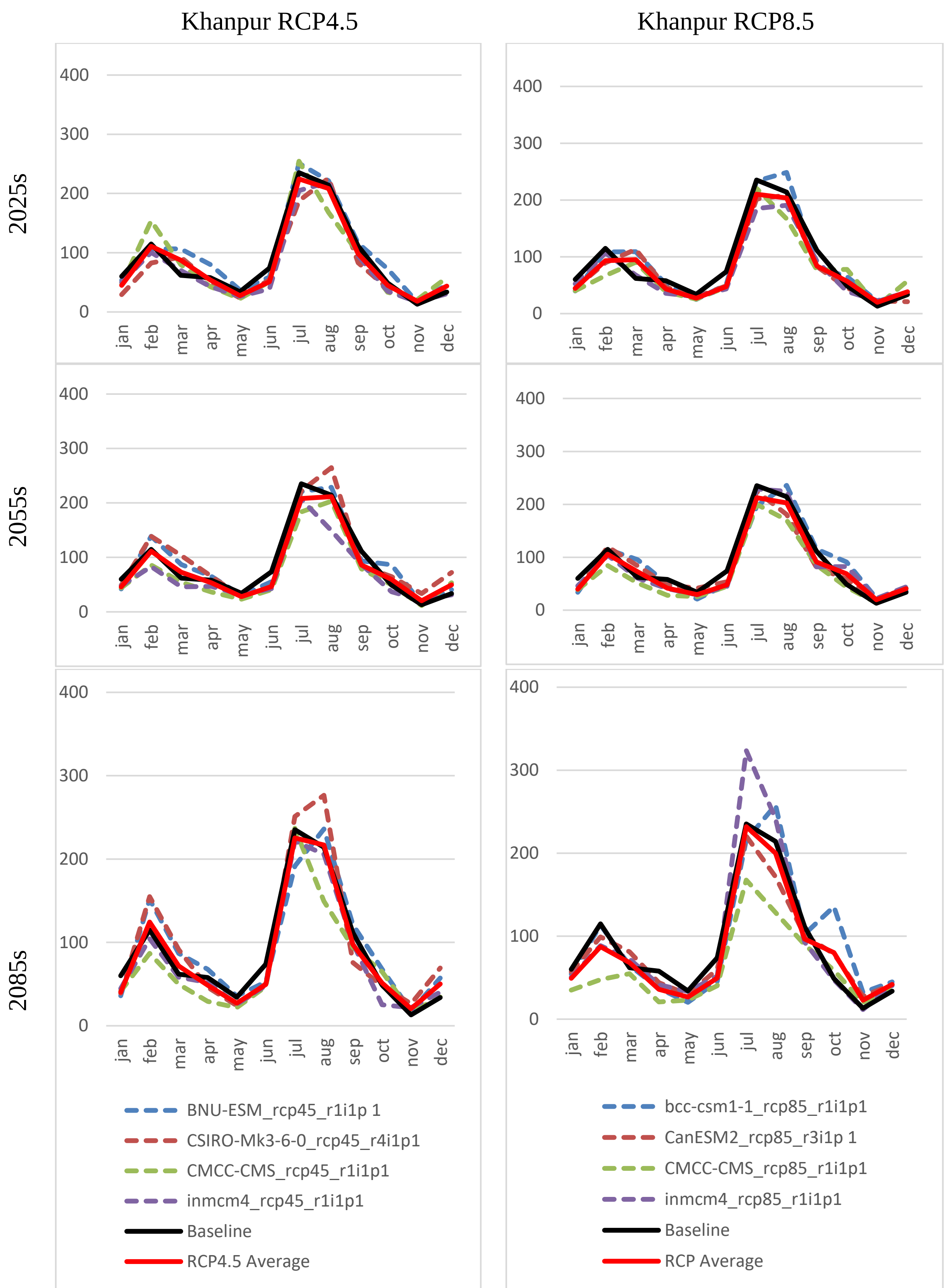

Figure 4-16: Projected changes in Precipitation at Khanpur Station

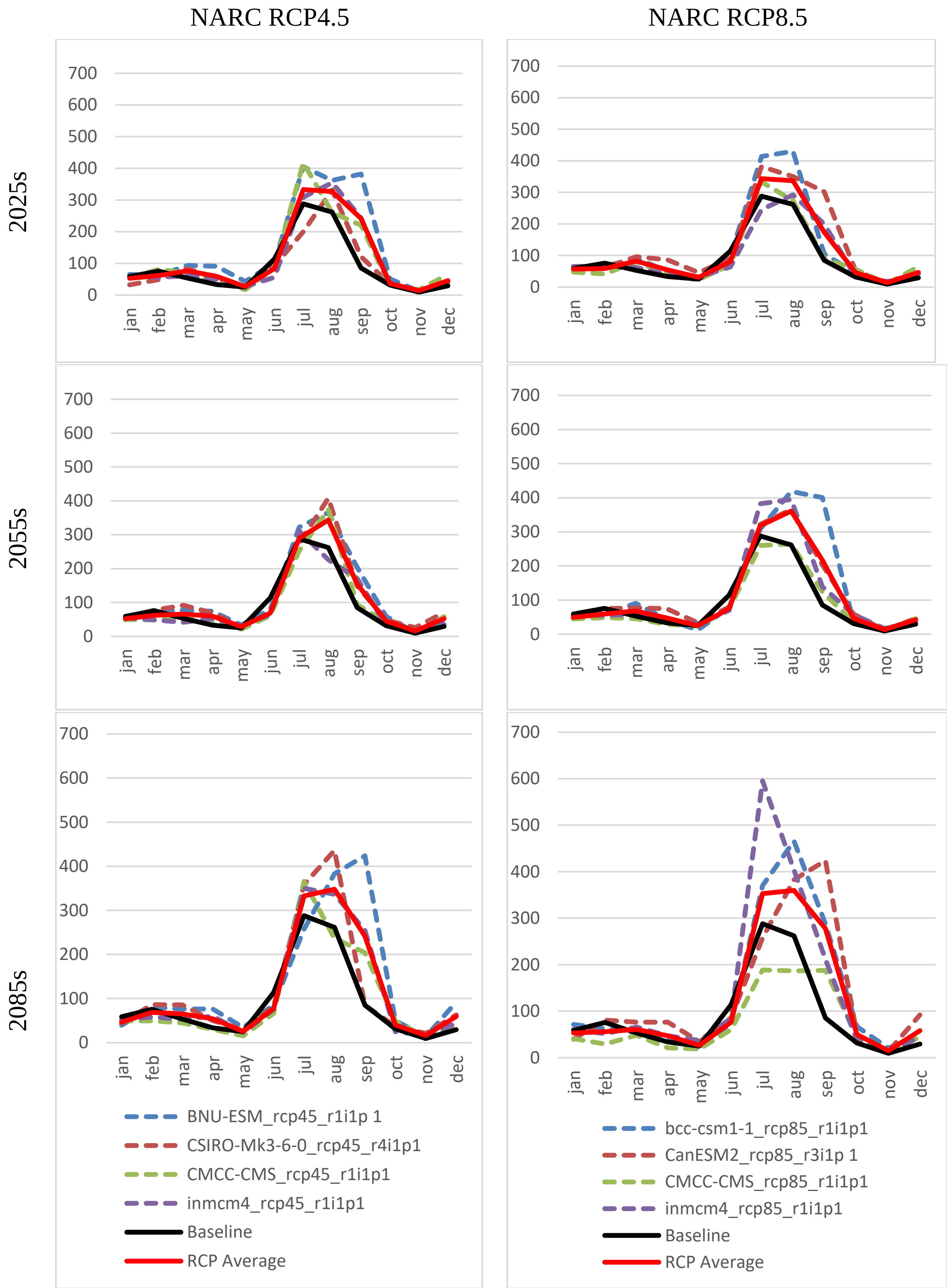

Figure 4-17: Projected changes in Precipitation at NARC Station

The future precipitation changes at Rawalpindi climate station depicts that under RCP4.5, the behavior of climate model is BNU_ESM_rcp45 is much noticeable with increase in precipitation for monsoon period but a considerable increase in precipitation for month of September for 2025s and 2085s except 2055s where change is no much high. All the other three models under RCP4.5 do not show much variation from baseline but also not strictly follow baseline. Alike to other climate station under RCP8.5, the projected trend of precipitation of climate model bcc_csm1-1_rcp85 is noticeable. The model predicts increase in precipitation for monsoon period with larger changes in month of September for 2055s. very likely to Rawal climate station, the behavior of inmcm4_rcp85 for Rawalpindi climate station is not different, which predicts gradual increase in precipitation from 2025s (less than baseline) to 2085s (more than baseline) for monsoon period predicts gradual increase in precipitation from 2025s (less than baseline) to 2085s (more than baseline) for monsoon period.

The projected changes in precipitation at climate station Chirah, the climate models output presents similar trend of precipitation for the time of the year as happened in baseline time period. Under RCP4.5, the climate model BNU_ESM_rcp4.5 varies with, comparatively, larger changes in precipitation trend than baseline especially period of 2025s and this change shows larger change in precipitation for month of April, July and September particularly. Under RCP8.5, the climate model's projections are much like above discussed climate stations. As bcc_csm1-rcp8.5 shows considerable increase in precipitation for month of July in 2025s and for month of September in 2055s. There is also gradual increase in projected precipitation by inmcm4_rcp85_r1i1p1 from 2025s to 2085s.

At Chaklala climate station, the projected changes in precipitation for month June and July, under both climate change scenarios, is worth mentioning that all the models till end of the century show negative trend. For rest of the year, al the models predict similar natured behavior as followed be baseline but with little variation.

The precipitation at Simly climate station for baseline period shows that July is the month of the year having maximum precipitation comparing to any other month. For climate change scenarios, RCP4.5 and RCP8.5 , the trend is much similar but with little variation at monthly basis. Under RCp4.5, where the climate CSIRO-MK3-6-0, shows gradual increase in precipitation from period 2025s to 2085s, the climate model CMCC-CMS_rcp45 predicts a gradual decrease in precipitation for same time window. under RCP8.5, bcc-csm1_1 is the model predicting maximum precipitation for monsoon period (July and August) comparing to any other model for 2025s, whereas for 2085s, inmcm4_rcp8.5 shows maximum precipitation prediction for month of July.

At Johrabad climate station, it is observed that all the climate models under both climate change scenarios , RCP4.5 and RCP8.5, prediction decrease in precipitation for month of June and increase in precipitation for month of march.

There are two precipitation peaks in hydrograph of Chakwal climate station, one is post winter season and other is for monsoon period. The climate change projections under both climate change scenarios RCP4.5 and RCP8.5 , presents a different behavior than baseline. The most prominent is that all the models are predicting decrease in precipitation for month June. Also, the outputs of climate models show that only few models predict increase in July precipitation for all time windows 2025s, 2055s 2085s.

At Khanpur climate station, under RCP4.5 the climate model CMCC-CMS_rcp45 predicts an increase in precipitation from baseline for winter season of time window 2025s but decrease in precipitation for 2085s similar time of the year. Under same climate change scenario, the CSIRO-Mk3_6_0_r4i1p1 is the model predicting gradual increase in precipitation from 2025s-time window to 2085s. It is also observed that under both climate change scenarios there is decreasing trend of precipitation for month of June. Under RCp8.5 bcc_csm1-1_rcp85_r1i1p1 predicts August is the month to have maximum precipitation in future till end of the century. For same climate change scenario, inmcm4_rcp85_r1i1p1 predicts that for time window 2085s, the maximum precipitation may happen in the month of July i.e. pre-monsoon period.

The precipitation at NARC station for baseline period depicts that maximum precipitation of the year happens in the months of monsoon from July to August. The projections under RCP4.5 climate change scenario shows increase in precipitation for the same months. Also, the increase in precipitation for August is higher comparing to any other month. Under RCP8.5, similar trend of change in precipitation is predicted by climate models with dissimilarity from each other from month to month and time windows. Under RCP8.5, CanESM2_rcp85_r3i1p1 predicts a considerable increase in precipitation for month of September especially in time window 2055s. Similarly, CMCC-CM5_rcp85_r1i1p1 is the model predicting highest change in precipitation for the month of July for 2085s.

Here, it is worth noting that individual behavior of the models cannot guide very well for future predictions. However, average of models under two different scenarios can be used for understanding of upcoming changes in precipitation patterns and quantity. Table 4-3 and Table 4-4 explain the predictions of precipitation under RCP4.5 and RCP8.5 at seasonal and annual bases and their variation from baseline (observed data) for 11 precipitation stations in Table 4-5 and Table 4-6. Seasons are defined here as winter starting from Nov to Feb, Spring lies from Mar to Apr, Summer is from May to Jun, Monsoon from July to Aug) and Autumn consist of two months (Sep-Oct). Table 4.6 present projected change in averagely distributed precipitation in the Soan catchment.

Average precipitation over Soan catchment in Table 4-7 showed decrease in Summer and Monsoon precipitation during 2025s and 2055s and during 2085s there increase during Monsoon under both emission scenarios RCP4.5 and RCP8.5 . Winter and Spring showed increase in precipitation throughout the century during RCP4.5 while Autumn showed little decrease during mid-century. Overall annual results showed decrease in rainfall during 2025s and 2055s while increase during 2085s under RCP4.5. Under RCP8.5 Winter precipitation is increasing, Spring is gradually decreasing, and Autumn is gradually increasing throughout the century. Annual precipitation trend showed decrease in precipitation under RCP8.5.

Table 4-3 Seasonal precipitation at 11 gauging stations under RCP 4.5

Precipitation (mm)			Murree	Islamabad	Rawal	Rawalpindi	Chirah	Chaklala	Simly	Joharabad	Chakwal	Khanpur	NARC
Seasons	2025	Winter	99	45	50	46	64	44	44	18	34	54	44
		Spring	167	69	68	72	98	56	69	35	49	71	68
		Summer	108	55	54	54	68	26	65	21	36	39	55
		Monsoon	298	333	312	338	267	220	239	87	110	217	330
		Autumn	149	111	122	127	108	57	53	20	23	72	139
		Annual	153	110	109	114	112	74	86	33	48	85	113
	2055	Winter	96	46	48	47	65	47	45	19	35	57	46
		Spring	133	62	63	66	88	51	62	31	42	63	63
		Summer	103	49	40	49	61	23	62	20	35	37	49
		Monsoon	306	319	313	316	259	225	236	79	109	210	317
		Autumn	123	86	85	90	83	54	52	18	24	73	100
		Annual	143	101	100	102	104	75	84	31	47	83	103
	2075	Winter	102	47	47	47	65	51	46	20	38	59	48
		Spring	125	60	57	63	72	55	61	31	43	60	60
		Summer	101	51	43	51	59	25	64	20	35	38	52
		Monsoon	325	348	325	343	284	228	248	90	119	221	340
		Autumn	165	114	125	124	104	58	55	20	25	74	141
		Annual	153	111	107	113	108	78	87	34	50	85	115

Table 4-4 Seasonal precipitation at 11 gauging stations under RCP 4.8

Precipitation (mm)			Murree	Islamabad	Rawal	Rawalpindi	Chirah	Chaklala	Simly	Joharabad	Chakwal	Khanpur	NARC
Seasons	2025	Winter	90	46	45	48	59	39	41	17	32	49	44
		Spring	133	61	57	75	87	57	67	32	49	69	69
		Summer	101	52	48	57	65	25	62	20	37	37	56
		Monsoon	311	332	332	334	267	224	231	81	113	207	340
		Autumn	124	89	104	88	81	54	49	18	23	70	110
		Annual	141	104	105	108	103	73	82	31	48	80	110
	2055	Winter	89	42	44	46	59	43	40	18	34	51	41
		Spring	108	56	56	64	70	47	56	27	41	57	58
		Summer	104	54	50	61	68	26	64	21	39	39	50
		Monsoon	308	339	334	332	264	222	235	85	118	208	340
		Autumn	148	95	107	104	98	54	54	20	26	80	132
		Annual	141	104	106	109	103	72	82	32	49	81	110
	2075	Winter	92	45	43	49	61	41	42	17	34	50	46
		Spring	98	49	43	58	67	43	52	22	38	52	54
		Summer	103	55	49	62	66	27	63	21	38	38	52
		Monsoon	325	380	398	370	278	227	247	81	113	216	356
		Autumn	178	120	145	132	115	61	63	22	28	88	164
		Annual	148	116	120	120	108	74	85	30	48	82	119

Table 4-5 Seasonal variation in precipitation at 11 gauging stations under RCP 4.5

Precipitation (mm)			Murree	Islamabad	Rawal	Rawalpindi	Chirah	Chaklala	Simly	Joharabad	Chakwal	Khanpur	NARC
Seasons	2025	Winter	3	-2	5	-1	22	4	-4	3	2	-1	0
		Spring	18	1	9	-1	39	1	10	9	8	11	25
		Summer	-3	0	0	2	25	-25	-18	-19	-29	-15	-14
		Monsoon	-17	26	-3	14	12	-16	-6	3	-14	-8	55
		Autumn	49	45	48	55	38	-5	-6	-5	-2	-8	81
		Annual	9	11	11	11	26	-6	-5	-1	-5	-4	25
	2055	Winter	-1	-1	3	0	23	8	-3	4	3	1	2
		Spring	-15	-6	4	-7	30	-4	3	5	1	3	19
		Summer	-9	-6	-14	-3	18	-28	-22	-20	-30	-17	-21
		Monsoon	-9	12	-2	-7	4	-10	-9	-5	-14	-15	42
		Autumn	22	20	11	18	13	-8	-7	-6	-1	-8	41
		Annual	-2	3	1	0	18	-6	-7	-3	-6	-6	14
	2075	Winter	6	0	3	0	23	12	-2	5	7	3	4
		Spring	-23	-8	-2	-10	13	0	2	5	1	0	16
		Summer	-10	-4	-11	-1	16	-25	-20	-20	-29	-16	-18
		Monsoon	10	42	10	20	28	-7	3	6	-5	-4	66
		Autumn	65	48	51	52	34	-4	-4	-4	0	-6	83
		Annual	9	13	9	10	23	-2	-4	0	-3	-3	26

Table 4-6 Seasonal variation in precipitation at 11 gauging stations under RCP 4.8

Precipitation (mm)			Murree	Islamabad	Rawal	Rawalpindi	Chirah	Chaklala	Simly	Joharabad	Chakwal	Khanpur	NARC
Seasons	2025	Winter	-6	-1	0	1	17	0	-7	2	0	-6	1
		Spring	-15	-6	-2	3	28	2	7	6	8	9	25
		Summer	-11	-4	-7	6	22	-26	-21	-19	-28	-17	-14
		Monsoon	-5	25	17	11	11	-11	-14	-3	-11	-18	65
		Autumn	23	24	30	16	11	-8	-10	-6	-2	-10	52
		Annual	-3	6	6	6	18	-7	-9	-3	-5	-8	22
	2055	Winter	-8	-5	-1	0	17	3	-8	3	2	-4	-2
		Spring	-40	-12	-3	-9	11	-9	-3	1	0	-3	15
		Summer	-7	-2	-5	9	25	-25	-20	-18	-26	-15	-19
		Monsoon	-7	32	19	9	8	-14	-10	1	-6	-17	65
		Autumn	47	30	33	32	28	-8	-5	-4	1	0	73
		Annual	-4	6	7	7	18	-8	-9	-2	-5	-7	21
	2075	Winter	-4	-2	-2	2	19	2	-6	2	3	-5	2
		Spring	-50	-19	-16	-14	8	-12	-8	-4	-3	-8	11
		Summer	-8	-1	-5	11	23	-24	-21	-18	-27	-16	-18
		Monsoon	10	74	83	47	22	-9	2	-3	-11	-9	81
		Autumn	77	54	71	60	45	-1	3	-2	3	8	105
		Annual	4	18	21	18	23	-7	-6	-4	-6	-6	31

Baseline (1983-2010)		Murree	Islamabad	Rawal	Rawalpindi	Chirah	Chaklala	Simly	Joharabad	Chakwal	Khanpur	NARC
Seasons	Winter	96	47	44	47	42	39	48	15	32	55	43
	Spring	148	67	59	73	59	55	60	26	41	60	43
	Summer	111	56	55	52	43	51	83	40	65	54	69
	Monsoon	315	306	315	323	256	236	245	84	124	225	275
	Autumn	100	65	74	72	70	62	59	24	25	80	58
	Annual	144	98	99	102	85	80	91	34	53	88	89

Table 4-7 Seasonal Change in averagely Distributed Precipitation in the Soan Catchment

	Seasons	RCP4.5		RCP8.5	
		Absolute	Deviation	Absolute	Deviation
2025	Winter	41	0.0	41	-0.3
	Spring	64	7.4	61	5
	Summer	42	-19.3	41	-20
	Monsoon	200	-8.7	202	-7
	Autumn	59	5.9	52	-1
	Annual	75	-1.5	73	-4
2055	Winter	46	4.7	42	1
	Spring	56	-0.2	51	-5
	Summer	39	-22.3	43	-19
	Monsoon	200	-8.9	203	-6
	Autumn	52	-0.4	57	4
	Annual	73	-3.7	73	-4
2075	Winter	49	7.6	43	1
	Spring	56	-0.3	47	-10
	Summer	40	-20.9	43	-19
	Monsoon	210	1.4	210	1
	Autumn	60	7.7	66	13
	Annual	77	0.5	75	-2

Baseline (1983-2010)	Basin Average (mm)
Winter	40.7
Spring	56
Summer	61.0
Monsoon	208.6
Autumn	53
Annual	76.1

4.5 Climate Change Impact Assessment on Water Availability at Dhok Pathan

Figure 4-18 shows projected stream flows under RCP8.5 and RCP 4.5 emission scenarios. It provides information to understand behavior of individual model and average of 4 GCMs under each emission scenario. Observed (baseline) discharge shows highest values during monsoon season i-e July and August. RCO 4.5 predicts two flow peaks, one is post winters and other is post summers throughout the century. BNU-ESM_rcp45_r1i1p 1 shows slight deviation during the month of September in 2025’s tome window, otherwise following the trend. CSIRO-Mk3-6-0_rcp45_r4i1p1 agrees with the observed trend showing lowest discharge during May and highest value in August. CMCC-CM5_rcp45_r1i1p1 and inmcm4_rcp85_r1i1p1 predict good agreement with baseline with higher values during July and august throughout the century. bcc-csm1-1_rcp85_r1i1p1 predict highest value in September during 2055’s slice. CanESM2_rcp85_r3i1p1 predicts deviation with highest value in September during 2085’s period. CMCC-CM5_rcp85_r1i1p1 predict best fit throughout the century. inmcm4_rcp85_r1i1p1 follows the trend during 2025s, 2055s and 2085s slices. The projections under RCP 8.5 showed two peaks during 2025’s and 2055’s time slice. Overall results predict highest values of discharge during monsoon season (July and August) and CSIRO-Mk3-6-0_rcp45_r4i1p1 predict highest value of discharge during the month of August.

However, Table 4-8 is developed to present future water availability for five seasons and annual average. Results showed projected stream flow follow baseline trend throughout the century under both emission scenarios RCP45 and RCP85. Increase in stream flow during Monsoon is higher and Winter season also showed increase. Overall annual average showed increase in stream flow throughout the century for RCP4.5 and RCP8.5.

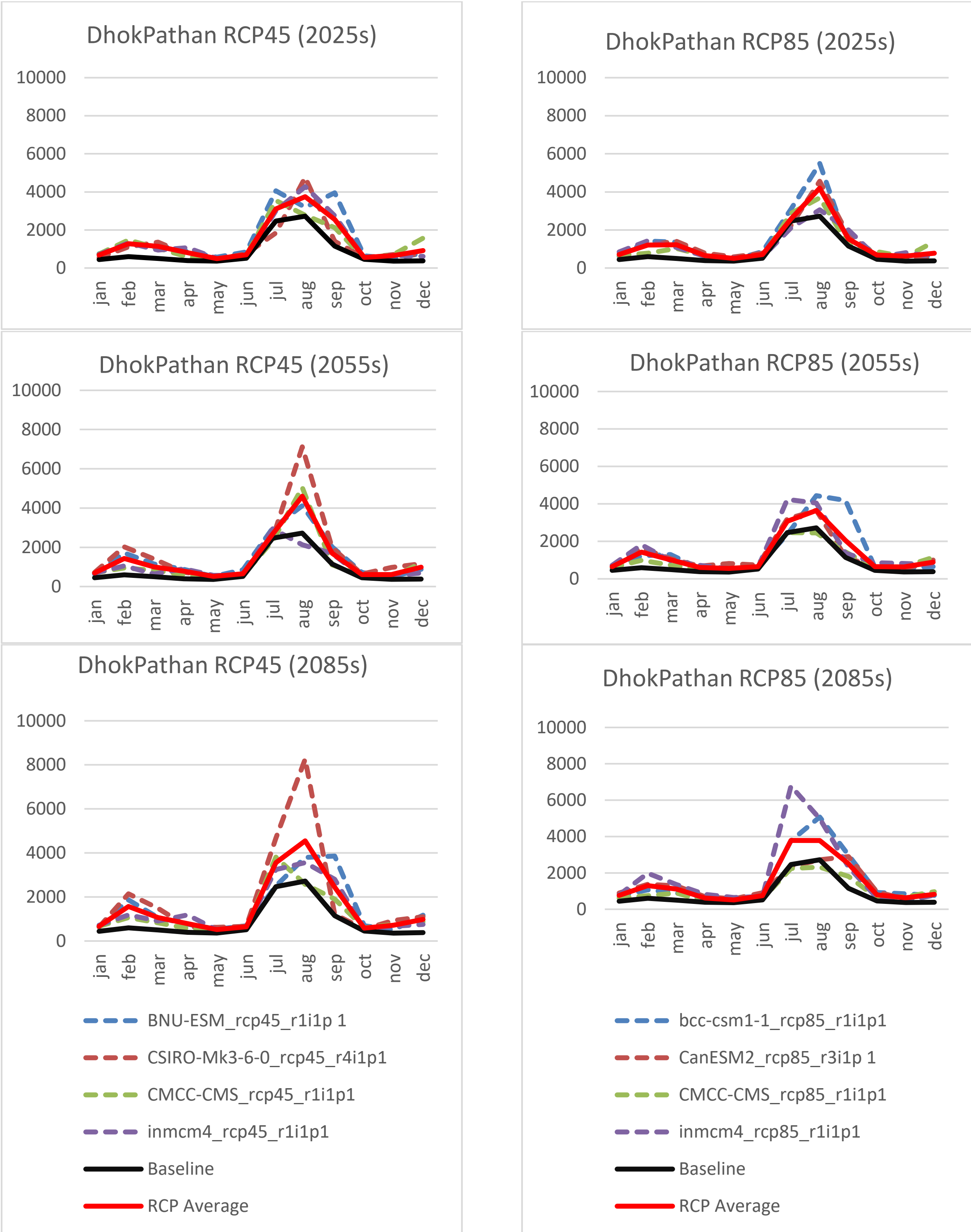

Figure 4-18: Climate change impacts on stream flow at Dhok Pathan

Table 4-8 Seasonal Variation in Stream Flow at Dhok Pathan under Climate Change

	Seasons	RCP4.5		RCP8.5	
		Absolute	Deviation	Absolute	Deviation
2025	Winter	880	433	829	381
	Spring	971	526	936	490
	Summer	597	79	607	167
	Monsoon	3430	837	3388	795
	Autumn	1556	754	1098	295
	Annual	1386	523	1281	418
2055	Winter	928	480	900	452
	Spring	890	445	817	371
	Summer	587	147	607	167
	Monsoon	3642	1049	3360	767
	Autumn	1152	350	1350	547
	Annual	1355	492	1322	459
2075	Winter	981	534	879	432
	Spring	929	483	863	417
	Summer	584	144	630	190
	Monsoon	4053	1460	3779	1186
	Autumn	1516	714	1647	845
	Annual	1507	645	1446	584

Baseline (2010-2013)	Stream Flow (m^3/sec)
Winter	447
Spring	446
Summer	440
Monsoon	2593
Autumn	802
Annual	863

4.6 Probable Maximum Precipitation (PMP) & Probable Maximum Flood (PMF)

PMP Values were calculated using statistical approach through Hershfield formula. For calculation purpose, all 11 stations data were used for PMP calculation. Km factor was calculated for various stations. Using the highest value of Km factor standard as 8.732, 24-hr PMP values were computed for all 11 stations along with ratio of PMP value to highest observed value are shown in Table 4-6. Figure 4-19 show the spatial interpolation of PMP values over the area using Kriging Interpolation technique.

Table 4-9: 24 Hours PMP Values

Station	Years	Mean X_n	St. Dev (S_n)	X_m	X_{n-1}	S_{n-1}	K_m	24 Hr PMP (mm)	Cv
Chakwal	8	65.06	28.95	106.2	59.19	25.60	1.84	317.87	0.44
Islamabad	30	120.50	50.29	243	116.27	45.45	2.79	559.70	0.42
Murree	35	119.21	46.67	255	115.21	40.85	3.42	526.75	0.39
Rawal	31	129.07	82.52	501	116.24	44.06	8.73	849.65	0.64
Simly	11	84.93	42.24	195.8	73.84	21.90	5.57	453.76	0.50
Rawalpindi	26	132.91	72.27	334.6	124.84	60.64	3.46	763.98	0.54
Jouharabad	8	71.21	19.40	95	67.81	18.21	1.49	240.67	0.27
Chirah	16	62.82	28.49	108	59.81	26.72	1.80	311.57	0.45
Khanpur	11	111.74	51.51	237.49	99.16	31.86	4.34	561.54	0.46
Chaklala	40	116.64	48.58	258	113.02	43.39	3.34	540.88	0.42
NARC	15	108.30	53.14	231.26	99.52	42.37	3.11	572.39	0.49

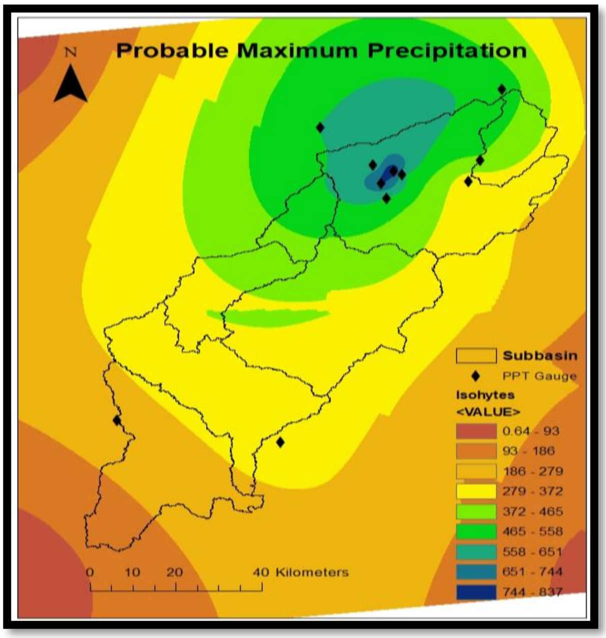

Figure 4-19 Spatial Representation of PMP Values

Using the values of PMP, as inputs for validated HEC-HMS model, PMF value was calculated for Dhok Pathan Station as 14138 cumics.

CHAPTER 5

CONCLUSIONS AND RECOMENDATIONS

5.1 Conclusions

- First part of this study was to identify land cover, which was done by processing Landsat imagery using ERDAS Imagine tool. Comparison of both classified images of 2004 and 2010 shows that major changes are happening in catchment. There is a huge decrease in forest and barren land and rise in urbanized area. Increase in built up land and decrease in forest cover may aggravate hydrological behavior of the catchment. Water bodies of catchment increased by 1.6% which is due to construction of small bunds in rural areas mostly for irrigation purpose.
- Hydrological model, HEC-HMS was calibrated for four years using daily precipitation and flow data at Dhok Pathan and validated for three years to see climate change effect assessment on river flow of Soan river catchment.
- Hydrological soil groups of soan catchment was found using FAO world soil map. Soan map contain two hydrological soil groups i-e B and C.
- Curve number values of the soan catchment varies from 58 to 100.
- HEC-HMS model was first calibrated and then validated for daily precipitation and channel flow data of seven years (2007-2013). Statistical analysis showed good correlation among observed and HMS simulated flow. Validated model of HEC-HMS was utized to calculate PMF and to predict stream flows at Dhok Pathan using climate data set.
- PMP values were calculated using Hershfield statistical technique for all 11 rainfall stations. PMF value was calculated through validated HEC-HMS model at Dhok Pathan station as 14138 cumics.
- Preliminary analysis of observed precipitation showed maximum precipitation during monsoon season in summers and in February during winters. Mean annual streamflow showed slightly increasing trend.

- Assessment of climate change was done using HI-AWARE Climate dataset based on 8 GCMs statistically downscaled at 10 km x 10 km resolution spatial grid. Bias correction was applied using Delta downscaling technique based on observed and baseline by overlapping historical data for new gauges. Bias corrected data for 3 time slices i.e. 2025s, 2055s and 2085s for 11 stations i.e. Chaklala, Islamabad, Rawalpindi, Chirah, Murree, Jouharabad, Khanpur, Chakwal, Simly, Rawal and NARC was compared with observed data and average model conditions.
- Analysis of biased corrected precipitation climate data of 2010 – 2100 showed overall increase in precipitation at all the 11 stations under both scenarios RCP45 and RCP 85.
- Seasonal analysis showed potential increase in precipitation during winter season, Monsoon showed decrease during 2025 and 2055 while increase during 2085 under RCP45 and RCP 85. Spring and Autumn precipitation increase throughout the century under RCP45 while RCP85 predicted increase in 2025 time slice and gradual decrease during Spring season. Under same scenario model predict increasing trend during Autumn precipitation.
- Both scenarios RCP45 and RCP 85 indicate the potential increase in stream flows at Dhok Pathan and follows baseline trend that could considerably lead to raise the water resources of the catchment under the changing climate. So, large and small storage reservoirs are essentially required to manage and cater the flood conditions in Soan River catchment.

5.2 Recommendations

- Hydrological Modelling in HEC-HMS involved terrain processing using 30m DEM and soil data was processed from world soil map which was readily available through open source. It is strongly recommended that fine resolution DEM i.e. 2.5m or 5m spatial resolution and local soil map of fine information may be used in future studies for better results.
- Some other hydrological model should be used to compare results of HEC-HMS.
- Climate change impact assessment should be done using gridded data too.

- For policy makers and stakeholders, a study should be conducted for adaptation strategies to changing climate.
- Acquisitions of data stream flow from various sources was a time consuming and laborious process. It is strongly recommended that a central database may be established where all the pertinent data along with all relevant studies may be complied and archived. This practice will be highly beneficial for guidance of future researchers to undertake their research in a befitting manner.
- Acquisition of climate data from HI-AWARE portal for 8 models from 2010 to 2100 and reference data was also laborious and time consuming. Therefore, HI-AWARE need to improve Regional Database System (RDS) to conserve time and fatigue

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