HYDROLOGICAL RESPONSE TO CHANGING CLIMATE FOR WATER AVAILABILITY- A CASE STUDY OF RAWAL DAM

BY

FATIMA MOBEEN

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This is to certify that the

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Dr. Shakil Ahmad

Assistant Professor

NUST Institute of Civil Engineering (NICE)

School of Civil and Environmental Engineering (SCEE)

National University of Sciences and Technology (NUST)

THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS thesis written by **Ms. Fatima Mobeen ,**Registration No **NUST201362216MSCEE15313F,** of MS Water Resources Engineering and Management 2013 Batch (NICE) has been vetted by undersigned, found completed in all respects as per NUST Statutes/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have been incorporated in the said thesis.

Signature________________________________

Name of Supervisor Dr. Shakil Ahmad

Date: ___________________________________

Signature (HoD) ____________________________

Date____________________________________

Signature (Dean/Principal)____________________

Date: ____________________________________

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HI-AWARE*: The projected future climate change studied in this thesis was completed with the help of the data acquired from Himalayan Adaptation, Water and Resilience (HI-AWARE) consortium.*

(Fatima Mobeen)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Hydrological modeling at catchment scale has been used in this study to analyze the effect of climate change on Rawal Dam, one of the main sources of water supply to twin cities of Rawalpindi and Islamabad. A suitable hydrological model had to be applied to simulate the hydrological response of Rawal Dam catchment to historical precipitation and later on, the calibrated model had to be utilized to assess climate change and its impact on reservoir inflows. HEC-HMS was used to effectively apply a rainfall-runoff hydrological model which distributed the watershed of Rawal Dam into 4 sub-basins each having different characteristics. Two climate stations i.e., Murree and Rawal Dam covered the whole catchment area of the reservoir. The simulation period of model was divided into calibration (1993-1996) and validation (2001-2004) periods. Parameters of the model were adjusted after calibration on a daily time step and the calibrated model was then utilized for validation of the simulation. The model provided a good fit between observed and simulated reservoir levels. Climate change projections of precipitation under Representative Concentration Pathways 8.5 and 4.5 were then used, after bias correction, as input to calibrated model to assess potential impacts of climate change on Rawal Dam. The analysis were performed on seasonal basis for three time windows 2011-2040 (2025s), 2041-2070 (2055s) and 2071-2100 (2085s), collectively which covered the current century. Baseline data from 1983-2010 was used. Projected precipitation at Rawal dam, Murree and basin wide were assessed. The results show increase in precipitation under both emission scenarios. Precipitation and as a result inflows projected to increase in all seasons i.e., Winter (Nov-Feb), Summer(May-June), Monsoon (July-Aug) and Autumn (Sep-Oct) except for Spring (Mar-Apr) where it is projected to decrease. RCP8.5 depicted a 12%, 10%, 18% increase in precipitation over Rawal dam catchment during 2025s, 2055s and 2085s respectively while RCP4.5 showed 21%, 6%, 8% increase in precipitation during the same time windows. RCPs differed in their results during start and end of the century while for mid of the century their results remained same. It was established that increase in flows is expected in future. Moreover, it was also found out that the calibrated model can be used satisfactorily for further hydrological impact studies on the reservoir.

Chapter 1

INTRODUCTION

1.1 BACKGROUND

River Indus is the 21st largest river in the world with an annual flow of 207km³. It is the longest and national river of Pakistan. Soan river is a tributary of Indus river flowing through Pothohar region of Pakistan. Starting from the foothills of Patriata and Murree and following a big curve, Soan river falls into Indus river near Kalabagh proposed dam site. Kaurang river is a stream originating from Murree Hills and alongwith other streams from Margalla hills have been diverted to form Rawal Dam. Kaurang, being the outlet stream of Rawal dam, finally falls into Soan river near G.T road.

In Pothohar region, the agriculture is largely dependent on rainfall which is 15-20in per annum since the streams of Indus in this area are surrounded by ravine belts and are deep set. Rainfall makes the majority part of runoff in this region. Due to steep topography, availability of hills (elevation ranges from 1000-2000m), narrow gorges, sound rocky strata, high stream flows and storage capacity, this area is considered good for damming the water through construction of dams and reservoirs. Rawal dam is a part of this damming strategy and one of the main source of water supply to the residents of Rawalpindi and Islamabad.

Dams/reservoirs are constructed with a designed life which is normally 50 years. The factors affecting life span of a dam are deposition of silt, future water availability, expected urbanization, expected water use and various other economic and social factors. The present live storage capacity of reservoirs in Pakistan has decreased by almost 35% of their designed capacities. The overall capacity of the three largest water reservoirs i.e., Tarbela, Mangla and Chashma has dropped by 4.37 Million Acre Feet (MAF). The original live storage capacity of these reservoirs was 16.28 MAF but sedimentation has brought it down to 11.91 MAF. The situation is even worse in twin cities of Rawalpindi/ Islamabad due to excessive urbanization in the last two decades. Water level in these areas has reached dangerously low level and excessive pressure is building up on the already constructed reservoirs resulting in decreasing capacity.

The country's total water storage capacity is almost 30 days; far less than international standards of 120 days. Unless new reservoirs are built, Pakistan is estimated to become a water scarce nation by 2025 decreasing the per capita availability of water from $5300m^3$ in 1950's to less than $1000m^3$ today which is considered as a scarcity benchmark. On the other hand, a report by Water and Power Development Authority (WAPDA) suggests that the country has a potential to store 17.8 MAF of water in future. The prediction of good inflow in future suggest a need to develop not only new reservoirs but also to enhance/improve the capacity of existing reservoirs.

A major factor affecting the storage capacity and efficiency of existing reservoirs is climate change. The average global temperature is expected to be rising by 0.2ºC for the next two decades. The elevated temperatures are expected to cause more evaporation resulting in a speedy "water cycle". This is expected to increase future precipitation. Studies have shown that average global precipitation is expected to be increasing from 3-5% with minimum increase of 1% and maximum of 8%. The rising temperatures would also tend to melt glaciers, ice sheets and other snow and ice cover on land. Even the sea ice on Arctic and Antarctic oceans is also expected to be decreasing. Severe weather changes like typhoon, floods hurricanes are expected to be seen in the future as a result of warmer oceans. The effect of these climatic variations on existing reservoirs would not be positive. As mentioned above, the storage capacity of reservoirs is decreasing by 0.8% every year. The sediment loaded or "filled up" reservoirs are not able to accommodate increasing precipitation or flood peaks.

Management of existing water reservoirs to accommodate future climate change is necessary keeping in view the fact that fewer feasible sites are now available for construction of reservoirs due to excessive urbanization, increasing population and degraded catchment areas. A proactive approach is required to evaluate the impact of climate change on reservoirs and to formulate adaptation strategies.

Internationally, extensive studies have been carried out to study the impacts of climate change on reservoirs. United States Bureau of Reclamation developed five different climate scenarios from one hundred twelve downscaled climate projections for Missouri River at Garrison dam. These scenarios were wetter and cooler, wetter and warmer, drier and cooler, drier and warmer a median future temperature and precipitation. Each Scenario was studied for two different periods i.e., 2010-2039 and 2040-2069. The data from the projected climate scenarios was used as an input for Variable Infiltration Capacity (VIC) model and value of infiltration, run-off and ground water percolation were derived. Later on, new elevation-storage relationship and reservoir inflows were developed for each climate scenario using VIC run-off values. These inflow and relationships were incorporated into Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) and Daily Routing Model (DRM) to model changes in the flow of stream and sedimentation transported to Garrison Reservoir. The results showed increase in reservoir pool elevation and releases for each climate scenario as compared to historical elevations and releases and it was contributed by increased inflows.

In the present study, HEC-HMS is used to analyze the effect of future precipitation on Rawal Dam. Since Rawal dam is the main source of water supply to the twin cities of Islamabad and Rawalpindi, its operation and future prediction of its storage capacity is very important for sustainable supply of water.

1.2 PROBLEM STATEMENT

Rawal dam, constructed in 1962, is the main source of water supply to the residents of Islamabad and Rawalpindi. The dam has completed its designed life of 50 years and sedimentation has decreased its live storage capacity significantly. The dam, constructed on Kaurang river, has catchment area of 273km². Margalla hills constitute the catchment area marked by rich vegetative cover and abundant precipitation. Recently, land use changes and urbanization has altered the catchment area to a vast extent. Moreover, increased sediment load and future water availability has put serious question marks on the capacity of reservoir and its reliability. The problem increases manifold keeping in view the increased population and the pressure it has put on the reservoir to meet industrial, agricultural, urban and environmental demands. Moreover, studies indicate increase in precipitation over the coming years. Catchment of Rawal dam needs to be checked for change in precipitation patterns.

1.3 OBJECTIVES OF THE STUDY

The study aims at investigating future projection of precipitation and its effect on storage of Rawal Dam.

The main objectives are:

1. Application of Rainfall-Runoff model for hydrological assessment of Rawal Dam catchment.
2. Assessment of change in precipitation under different climate change scenarios.
3. Projection of future water availability in the reservoir under climate change scenarios.

1.4 SCOPE OF THE STUDY

Documentation of catchment area characteristics and delineation of sub-basins along with spatial analysis is carried out. Hydrological modeling is then carried out to evaluate effects of recorded inflows on Rawal Dam. Climate change scenarios using Global Climate Models developed by HI-AWARE are developed and then utilized in hydrologic modeling to study the effect of future inflow on storage capacity.

1.5 RESEARCH METHODOLOGY

The following methodology has been adopted to carry out the study and analyze the results.

1. The basic control unit for planning and collection and computation of data has been selected as river basin of Rawal Dam. Two main precipitation stations have been selected for records which are Rawal Dam and Murree station.
2. Digitization of daily rainfall-runoff, spillway discharge, inflow and outflow data of Rawal dam and its catchment has been carried out using the records obtained from Small Dams Organization, the administrative authority of Rawal Dam.
3. Extraction of DEM for Rawal Dam catchment has been carried out
4. Documentation of water shed characteristics, performing spatial analysis and delineation of sub-basins and streams has been carried out using HEC GEOHMS and ARC-GIS.
5. The digitized data and delineated basin has been incorporated in HEC-HMS for hydrologic modeling of the reservoir. The study time extends from 1996-2004.
6. Sensitivity analysis of modeled parameters has been performed.
7. Future climate scenarios have been developed using HI-AWARE GCMs.
8. Future precipitation has been extracted for both precipitation stations and bias correction has been applied.
9. The behavior of reservoir has been studied using the data extracted from climate models in HEC-HMS.

1.6 DISSERTATION STRUCTURE

Chapter 1 covers the introduction of the study. The study area is briefly described. The major problems causing a threat to existing reservoirs are discussed. Scope of the study is defined and an overall view of the study is presented.

Chapter 2 covers literature reviewed for the present study bringing out the main points as

1. A brief description of water reservoirs in Pakistan and all over the world.
2. Future climate change and its impact on reservoirs.
3. Introduction to HEC-HMS and its applications

Chapter 3 describes the study area in detail covering the location, climate, topographic features, geological characteristics, land use, salient features of Rawal Dam etc.

Chapter 4 covers the methodology in detail. The framework adopted for study, the model developed and the tools utilized are described in detail.

Chapter 5 deals with the performance tests of the model, climate change projections and analysis of the results.

Chapter 6 deals with conclusions of the study followed by recommendations.

Chapter 2

LITERATURE REVIEW

2.1 GENERAL

Earth's water distributed through a network of oceans, rivers, streams and tributaries is mostly saline and exists in oceans. Only 2.5% of earth's water is fresh water available for sustainability of life. Of that 2.5% glaciers and ice caps trap almost 69% of fresh water while 30% is ground water. Only about 1.2% is surface water serving life's needs.

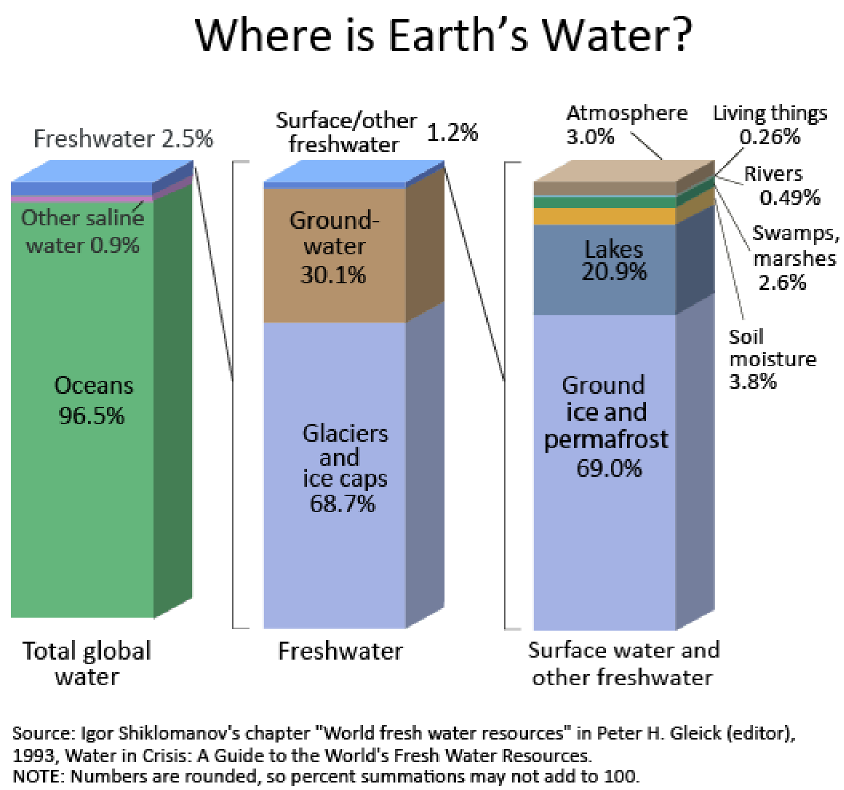

Figure 1: Availability of Earth's water

The available fresh water is not only "precious" in terms of availability but in terms of increasing demand. US Intelligence community assessment revealed in a report Global Water Security that by 2030 annual global water requirements would be 40% more than current sustainable water supplies. The result being, by 2030, almost half of the world will be living in highly water stressed conditions and the ones with developing economy or poor resource management would be suffering the most.

2.2 WATER RESERVOIRS AND THEIR STORAGE CAPACITIES IN PAKISTAN AND ALL OVER THE WORLD

Conserving water by building reservoirs and later on harnessing it for different purposes has been an important weapon of human against unpredictability of nature. In the last century only, 45000 dams have been built on the face of earth trapping almost 17% of global annual runoff and creating a combined storage capacity of 6700-8000km^3 [World Commission on Dams,2000; Chao et al., 2008; ICOLD, 2011]. With increasing population, more stress is likely to be created on future water demand and as a result more dams/reservoirs are likely to be built for irrigation, hydropower and other uses [Wisser et al., 2013].

According to Global Reservoirs and Dams Database (GRanD), which contains attributes of 6862 georeferenced reservoirs globally, the construction of reservoirs was at its peak during 1960's and 70's. Almost 150km^3 of storage capacity in 130 reservoirs was added annually at that time. The last decade (2001-2010) saw a decline in this trend where only about 15km^3 per year is being added annually now. Designed life of a reservoir is about 50 years on average. North America has relatively older reservoirs with an age of 60 years or more while Asia and Africa have younger reservoirs with the age of 40 years. Hydropower is still the main utilization of the installed capacity (64%) while irrigation covers 17% of the total capacity. The rest of the uses are flood control, water supply, recreation and others. Runoff of 53million km^2 is intercepted by these reservoirs which is 40% of total global land mass.

On the other hand, the storage capacities of already constructed reservoirs is constantly decreasing due to sedimentation and other problems. The demand for water is constantly increasing due to population growth and shortage of sites for construction of new reservoirs [Annandale, 2013].

According to International Commission on Large Dams (ICOLD), there are almost 42000 large dams on earth and many times as many small reservoirs. (ICOLD 1988). Globally, the total storage capacity of these reservoirs is more than 7000km³ while this storage is decreasing at the rate of 0.5-1% annually which means that 50km³ of storage has to be added annually to combat this loss. This added storage is going to cost $15 billion(2015 rate) [Palmeiri etal., 2003]

Moreover, some reservoirs trap more sedimentation than others and lose their storage capacities at a faster rate. Welbedacht reservoir in South Africa lost one-third of its designed storage capacity during 1st three years of its life. As a result, 86% of its storage volume was lost between 1973-2005 [Huffaker and Hotchkiss, 2006]. In Venezuela, Camare reservoir lost all of its storage capacity in 15 years due to sedimentation [Morris and Fan, 1998]. This shows that decrease in dam construction and sedimentation have joined hands with increasing population growth to aggravate the situation of water shortage all over the world [George, 2016].

Pakistan being an agrarian economy, is largely dependent on storage of its precious waters through dams and reservoirs. On average, Indus Plain in Pakistan receives 212mm rainfall in Kharif while 53mm of rainfall in Rabi season. During 1996-2006, Rawalpindi, for example received 1176mm while Islamabad received 1084mm of rainfall [Agricultural Statistics of Pakistan]. Pakistan has five main rivers namely Ravi, Beas, Sutlej, Chenab and Jhelum and three minor rivers namely Siren, Haro and Soan. All of these rivers join the main river Indus from the eastern side. On the western side, Kabul, Kunar, Punj, Kora, Gomal and various other small rivers join river Indus. On average, 101.9 MAF was the flow during 2002-07 for all the six major rivers in Kharif season while for Rabi it was 25.1 MAF during the same period [IRSA, Isb]. At the time of independence there were only three dams in Pakistan; Khushdil Khan dam, Spin Karazi dam and Nomal dam. Later on, in 1955, construction of new dams was started due to acute shortage of power and Warsak dam was constructed. When India tried to stop the waters flowing to Pakistan, two large dams were constructed; Mangla dam with the gross storage capacity of 5.88 MAF and Tarbela dam with a capacity of 11.62 MAF. Chashma Barrage was built with original storage capacity of 0.87 MAF. Pakistan has one of the best irrigation network in the form of Indus Basin Irrigation System consisting of 3 major reservoirs, 2 head-works, 16 barrages, 2 syphons, 44 canal systems, 12 inter river link canals. In addition to that, almost 80 small dams are also present in the country to meet the local demand of water. On average, 154 MAF of water is brought over by Indus and its tributaries. The western rivers contribute 144.91 MAF while the eastern ones contribute 9.14 MAF of water. Of this 154 MAF, 104.73 is used for irrigation, 39.4MAF flows back to the sea for environmental balance and almost 9.9 MAF is consumed by the system losses and evaporation etc. The figures, however, vary from year to year and also within a year. However, Pakistan is losing not only its storage capacity due to sedimentation but also the increasing population and salinity is putting stress on available supplies of water. In Karachi, particularly the situation is grave where the agricultural and urban demand is far greater than the supply due to dense population and lack of institutional capacity [Omar, 2004].

65% of total water flows in Pakistan are contributed by Indus while Jhelum and Chenab contribute 17 and 19% respectively. Monsoon, from June to August, is the period of peak flows wherein the flows for Kharif are 84% and for Rabi 16%. Small rivers and tributaries contribute almost no flow during winter months. It is therefore becomes necessary to store the waters during high-flow periods through management of water reservoirs [Kahlown and Majeed, 2003].

Statistics show that in the year 2013, population of the country was 207million while the per capita availability of water was 850m^3. the same is projected to be 659m^3 with an expected population of 221million. Going back to 1951, per capita availability of water was 5300m^3 [Draft state of Environment Report, 2005].

Table 1: Per Capita Water Availability in Pakistan

Per Capita Water Availability		
Year	Population (Millions)	Per Capita Availability (m^3)
1951	34	5300
1961	46	3950
1971	65	2700
1981	84	2100
1991	115	1600
2000	148	1200
2013	207	850
2025	221	659

Ten year perspective development plan 2001-11, released by Planning Commission reveals that in 2004 the available water for utilization was 104 MAF while the requirement was 115 MAF. In 2025, the available water would remain the same under the same scenarios while the requirement would be 135 MAF increasing the shortfall from 11 MAF in 2004 to 31 MAF in 2025. Construction of new dams or atleast increasing the storage capacity of existing dams is necessary for Pakistan keeping in view of the fact that after 1947 only two major reservoirs have been constructed here while India has, in the same time constructed 24 while Turkey has successfully constructed 65 new major reservoirs. 5 more reservoirs are in planning stage in Pakistan namely Basha Dam, Kalabagh Dam, Skardu Dam, Akhori Dam and Munda Dam. The construction of these dams is inevitable and should be initiated soon to avoid future shortage of water in the country [Ahmad et al., 2007].

Table 2: Storage Capacities of Planned Water Reservoirs in Pakistan

Name	Storage Capacity (MAF)		Installed Capacity (MW)	Status
	Live	Gross		
Basha Dam	6.4	7.30	4500	Engineering Design under preparation
KalaBagh Dam	6.10	7.90	3600	Ready for implementation
Skardu Dam	--	--	4000	Under feasibility study
Akhori Dam	3.60	7	600	Under feasibility study
Munda Dam	0.56	1	660	Engineering Design under preparation

Pakistan has to produce double of its annual food production every 15 years to meet its food demand. As a result, with 2.5% annual increase in population, the agricultural water demands are expected to rise from 188.28MAF in 2000 to 261.14 in 2025. Moreover, with per capita demand of $46m^3$ per annum, the domestic demand for water is expected to rise from 5.2MAF in 2000 to 9.7MAF in 2025. These demands can only be met by proper planning and management of water reservoirs in Pakistan [Kahlown and Majeed, 2003].

2.3 HYDROLOGICAL MODELING AND HEC-HMS

Hydrological Modeling is the most incredible phenomenon in the field of water resources. Sometimes it is just used to analyze the hydrological responses and phenomenon of a water resource. At other times, it is enforced and is used for timely prediction of flood, the demarcation of areas likely to be affected by flood, planning a water budget etc at regional and national scales [Razi et al., 2010].

There are several methods available to estimate generated runoff and its transmission to the designated outlet since usually very limited or no data is available to quantitatively assess the parameters. Design flood hydrograph and magnitude of flood peak can be estimated using Unit Hydrograph method and watershed models [Kalita, 2008].

Hydrological model simplifies the process of extensive calculations otherwise involved in prediction of hydrological response of a catchment or basin. In presence of a wide range of models available, the selection entirely depends on the type of catchment/watershed and the type of analysis required [Hunukumbura et al., 2008].

Hydrologic Engineering Centre-Hydrologic Modeling System (HEC-HMS) was developed by US Army Corps of Engineers that can be utilized for many hydrological simulations and their analysis [Feldman, 2000].

HEC-HMS, with the help of its tools like unit hydrograph, hydrologic routing, event infiltration, techniques required for continuous simulation of snowmelt, evapotranspiration, soil moisture accounting, gridded runoff simulation using ModClark, model optimization, depth area reduction etc. analyzes future water availability, urban drainage, flood forecasting, reservoir spillway operations, systems operation etc. [US Army Corps of Engineers].

HEC-HMS comprises four main components:

1. Advanced Graphical User Interface
2. Analytical model to calculate runoff as well channel routing
3. Tool for storing and managing data
4. Display and monitoring of outputs [Muthurkrishnan et al., 2006]

Nine different loss methods are available in HEC-HMS of which Initial and Constant Loss Method is simplest since it involves three parameters. 7 transformation methods are available. Long term stream flows have been successfully simulated using Synder Unit Hydrograph and Clark Unit Hydrograph [Yilma and Moges, 2007, Cunderlik and Simonovic, 2010].

Cunderlik and Simonovic (2004) worked on a water resources research report on the data from Upper Thames River Basin (UTRB) using HEC-HMS. The work described in-depth the calibration, validation and sensitivity analysis of HEC-HMS model and can be used along with Report II as a reference manual. Both event and continuous models were developed. In the event model, UTRb was sub-divided into 33 sub-basins using HEC-GeoHMS software. The river basin processes were divided into 6 main components namely Meteorological component (to spatially and temporally distribute rainfall data over the basin), Rainfall loss component (Initial and constant rate loss method), Direct Runoff Component (Clark Unit Hydrograph), River Routing Component (Modified Puls method), Baseflow component (Recession method), Reservoir Component (elevation-storage-outflow method). Calibration was performed both manually and automated and it showed that the simulation is ideal for intensive summer storm events since the autumn rainfall events require detailed information of movement and storage of water within the basin and are modeled with continuous model. In continuous model, evapotranspiration and soil moisture accounting are accommodated in addition to snowmelt and accumulation. Manual calibration was performed and spring flows, low flows and autumn rainfall events were focused. Validation of event models showed that the simulation was brilliant in peak flows while underestimated the flow preceding and succeeding the peak. Validation of continuous model performed well in dry periods of low flows, snow melt and summer and winter peaks. Sensitivity analysis showed that event model is sensitive to Clark Hydrograph, loss and baseflow recession while continuous model is sensitive to Clark Hydrograph, infiltration rate and soil layer storage.

Three different approaches were used by Halwatura (2013) to simulate hydrological response of Attanagalu Oya catchment using HEC-HMS 3.4. Daily rainfall data of 20 years from 5 different gauging station, monthly evaporation data for the same time period and daily flow data from 2005-2010 have been used in the study. Arc-GIS 9.2 was used to generate GIS layers for calibration of flow. The methods used were SCS Curve Number Loss method, Deficit Constant Loss Synder Unit Hydrograph method and Clark Unit Hydrograph method. The model was calibrated separately for the three methods to determine most suitable simulation. New rainfall and flow data from 2008-10 was used for model validation and relative error and residual performance tests were performed to statistically test the simulations. SCS curve number method turned out to be less useful than Deficit Constant Loss Method. Moreover, the results obtained through Synder's Hydrograph were more reliable than those for Clark Unit Hydrograph.

Verma et al., (2010) simulated Upper Baitarani River basin of Eastern India using HEC-HMS and WEPP (Water Erosion Prediction Project) hydrologic models. Daily monsoon (June-Oct) rainfall data for rainfall and corresponding streamflow data for 6 years (1999-05) were used for simulation. Remote sensing and GIS was used for soil map, land cover and slope map. The generated stream flows for the years 1999, 2002, 2004, 2005 turned out to be under predicted while for 2001 and 2003 the flows were over predicted by both HEC-HMS and WEPP. Percent deviation in HEC-HMS for runoff volume calculation varied from -2.55%-31% while for WEPP -13.96%-13.05% showing WEPP to be more reliable. However, the results of Root Mean Square Error, Nash-Sutcliffe coefficient, Percent Deviation and Coefficient of Determination decided in favor of HEC-HMS. The study concluded that stream flow simulation of the study area was better performed by HEC-HMS than WEPP.

Abushandi et al., (2013) simulated rainfall-runoff relations for an arid region, Wadi Dhuliel, in Jordan to develop a new framework of generated model applications by using satellite-derived rainfall data set (GSMaP_MVK+) to determine location of rainfall storm. HEC-HMS and IHACRES (Identification of unit Hydrographs and Component flow from Rainfall, Evaporation and Streamflow datas) were used for the simulation. A single stream flow event that occurred on 30-31/01/2008 was determined and hourly time step was used. The data required for HEC-HMS was soil type, land cover, land slope while the Java based lumped IHACRES required hourly rainfall and temperature data which was incorporated. Calibration and validation was performed for both models. Nash-Sutcliffe Efficiency test was done to check the performance of both models which give the values of 0.51 and 0.88 for IHACRES and HEC-HMS respectively. The study concluded that simulation was performed better by HEC-HMS than by IHACRES.

Choudhari et al. (2014) conducted simulation of rainfall-runoff for Balijore Nala watershed, India using HEC HMS. Runoff volume, peak runoff rate, base flow and flood routing were the hydrological parameters computed using SCS Curve Number, SCS unit hydrograph, Recession (exponential) and Muskingum Routing respectively. A time period of four years (2010-2013) was selected for rainfall-runoff simulation and 24 individual events were chosen. Data of 12 events was used for model calibration and remaining 12 were used for validation. Sensitivity analysis of calibrated model was performed using statistical tests of error functions between observed data and simulated data. Mean Absolute Relative Error (MARE) for Runoff depth was found to be 0.20 and for peak discharge to be 0.25. The value of Root Mean Square Error (RMSE) for runoff depth was 2.3mm while for peak discharge 0.28m³/s. The parameters were optimized and the same values reduced to 0.1, 0.12, 0.75 and 0.09 respectively. Optimized and calibrated simulation was then used for validation of results which came out to be satisfactory on sensitivity analysis. The same model can now be utilized to not only obtain runoff data in the water shed but also to simulate runoff in the un-gauged points.

Mona Lake in West Michigan, US was simulated to study hydrological response of the catchment to different rainfall events. Four rainfall events were selected for the study HEC-HMS was used for hydrological modeling. The model parameters were identified through calibration of data of individual events on fine scale. Later on, the same parameters were used in the continuous hydrological model that included a number of rainfall events and their cumulative effects over a longer duration. Soil Conservation Service (SCS) curve number was used for surface runoff calculation in event simulation while Soil Moisture Accounting method were used for the same calculation in continuous model. Two models were generated as a result and the relationship between both was analyzed. Moreover, the details about amount, unevenness and source of runoff in the catchment was obtained through simulation. The results indicated that if fine scale (5 min time step) is used along with intensive field data in event modeling, the continuous modeling can be improved in coarse scale (hourly time step) with the help of calibrated and optimized parameters [Chu et al., 2009].

Forecasting of runoff using precipitation forecasts for operation of reservoirs during flood was the main theme of hydrological modeling conducted by Anderson et al., (2000). Reservoirs of Seirra Nevada Mountains in California were selected for the study. NCEP eta model's precipitation forecast was used which gives the forecast 48 hours ahead in 6 hrs time interval in a appropriate time and space. HEC-HMS was used to convert the available rainfall in runoff and the successful results have been implemented in Calaveras Watershed in Central California Hammouri et al., (2007) carried out Hydrologic modeling of ungauged wadis in Jordan using GIS and HEC-HMS for the purpose of artificial groundwater recharge. Precipitation data of Intensity-Duration-Frequency curves for 10 years and 50 years return period were used. For 10 year return period, runoff volume came out to be 151,000m^3 and peak discharge to be 5.4m^3/s. For 50 year return period, the runoff volume was 280,000m^3 while peak discharge was 12.77m^3/s. Model optimization was performed against observed data using SCS curve number values from 78-86 and flow comparison was generated. Root mean square error of 2% was observed which shows the simulation to be good. The simulation showed that precipitation events of more than 14.3mm would generate runoff and runoff volumes less than 500,000m^3 from 40mm rainfall would be suitable enough for recharge.

Upper Euphartes Basin was simulated by Yilmaz et al., (2012) using HEC-HMS and Large Basin Runoff Model (LBRM). Precipitation, evapotranspiration and snow melt were the data input for HEC-HMS where the time period 1997-2002 was used for calibration and 2003-2004 for validation. In calibration Nash-Sutcliffe coefficient, Mean Squared Relative Error and Linear Regression gave the values of 0.7, 0.28, 0,7 respectively. In validation, the same checks valued to be 0.76, 0.18, 0.77 in the same sequence. Satisfactory simulation was performed by HEC-HMS. LBRM calculates daily available heat and the data required are daily temperature, daily precipitation, variable area infiltration and degree day snowmelt. The calibrated results were statistically tested like HEC-HMS and the values came out to be 0.73, 0.23,0.75 in the same sequence. For validation, the values were 0.72, 0.29, 0.75. In calibration, HEC-HMS did not perform better while LBRM lagged behind HEC-HMS in validation.

Subarnarekha river basin in Eastern India was simulated by Roy et al., (2013) using HEC-HMS for estimation of future available water. The basin was divided in three sub-basins after delineation of the study area form topographic maps and Google earth images. Thiessen Polygon method was used to estimate daily rainfall and temperature data while Penman's method for evapotranspiration input. Each sub-basin was classified into four classes namely water body, agricultural land, grass land and forest and hence the values of SMA parameters (canopy interception storage, depression storage, tension zone etc) were estimated. Stream flow hydrograph was generated using Clark unit hydrograph and Synder Unit Hydrograph, linear reservoir method was used for baseflow, Muskingum method for channel routing of discharge. The simulation was found to be sensitive to soil storage, tension storage and ground water storage coefficient. The performance indicators used were Nash-Sutcliffe model efficiency, Percentage error in volume, Percentage error in Peak, net difference of observed and simulated time to peak. The values ranged from 0.72-0.84, 4.39-19.4%, 1.9-19% and 0-1 day respectively. High coefficient of determination value (0.7-0.85) was obtained which shows good simulation.

2.4 FUTURE CLIMATE CHANGE STUDY AND ITS IMPACTS ON RESERVOIRS

A collection of statistics about weather for a duration of 30 years determine climate of a region. Several factors are involved which include variation in temperature, humidity, precipitation, wind, atmospheric pressure, etc. Prediction of future climate scenarios is important for sustainable planning of resources for human race on earth.

Intergovernmental Panel on Climate Change (IPCC) was established when World Meteorological Organization and United Nations Environment Program joined hands to assess scientific, technical and socio-economic information for understanding the risk of climate change induced by human. Since the time of its development, IPCC has released several assessment reports on possible climate change, its effects and adaptation strategies which act as a reference in various fields. To estimate the full suite of Green House Gases, IPCC released emission scenarios (description of how Green House Gas emission can evolve between 2000-2100 in 1992, called IS92, for Global Circulation Models for development of climate change scenarios. Later on Special Report on Emission Secnarios (SRES) was presented in 2000 to describe new emission scenarios. SRES 2000 was superseded in 2014 by Representative Concentration Pathways published in 5th assessment report (AR5) by IPCC. RCPs are four GHG concentrations, instead of emissions, trajectories.

RCPs are used for climate modeling and relative research. They represent four different possible future climatic conditions depending on the concentration of GHG emission in the upcoming years. The RCPs 2.6, 4.5, 6 and 8.5 are named after climate forcing values in 2100. Climate forcing means the difference between sunlight absorbed by earth surface and reflected back to the space. Positive value indicates that amount of absorbed light is more than the radiated back one. The value is quantified in watts per square meter of earth's surface. The GHG emissions are measured in CO2 equivalents. RCP 2.6 assumes peak emission of GHG between 2010-2020 and then recedes.RCP4.5 assumes it to be around 2040 and then decline. RCP 6 assumes peak emissions around 2080 and after that decline whileRCP8.5 assume it to be rising throughout the 21st century.

In the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4), the used climate models indicated a warmer trend in temperatures for 21st century in the Pacific Northwest. The models compare an average from 1970-99 to those of next century and predict an increase in annual temperature of 1.1ºC by 2020s, 1.8ºC by 2040s and 3ºC by 2080s. The rates of temperature rise vary from 0.1-0.6ºC per decade. The corresponding rates of precipitation are predicted to increase slightly i.e., 1-2%. Some of the models predicted wetter autumns and winters and drier summers. Sea-level rise would depend largely on ice sheet in Green land and Antarctica and may range from 20cm to 1.3m

Global warming increases the water retaining capacity of air by 7% per 1ºC warming thereby increasing water vapors in the atmosphere. This results in intense but less frequent precipitation events increasing flooding. Meager changes bring more precipitation in already wet areas while the dry areas become drier. Moreover, warmer temperatures tend to melt the snow cover and precipitation events involve rainfall and no snowfall resulting in flash floods [Trenberth, 2011].

Arnell studied the effect of future precipitation change on global water resources using Hadley Centre Climate Simulations and simulated global river flows using conceptual water balance hydrological model. He calculated the changes in national water resource availability and noticed some important regional variations and deduced that global warming would increase precipitation and evaporation but the precipitation would be distributed un-evenly. Average annual runoff is predicted to increase in higher altitudes, in Africa, Asia and South-East Asia but will decrease in moderate latitudes and sub-tropical regions. Moreover, spring snowmelt would be shifted to winter runoff. Most affected countries would be the ones around the Mediterranean, the Middle East and South Africa [Arnell, 1999].

Kopytkovskiy et al.(2004) studied the climate change impact on water resources and hydropower potential in Upper Colorado river basin. WARMF hydrologic model was derived using downscaled climatic projections. The climatic models used for the study were three, Japan's Meteorological Research Institute's MRI CGCM2.3.2 (MRI), Japan's MIROC3.2 (MIROC) and the Canadian Centre for Modeling and Analysis (CGCM3) under A2 and B1 emission scenarios.

The study revealed that future projections for precipitation vary upto 16% while flow projections varied by 50%. Temperature was projected to be increasing at lower elevations while higher elevations showed extensive seasonality and temperature in summers was found to be increasing at all elevations. Moreover, areas at lower elevations would be going to see reduction in precipitation while higher elevations would receive more pour and summer showed decreased precipitation without any discrimination of elevation.

Petra Doll (2002) studied the effect of climate change on future irrigation requirements using Global Irrigation Model (GIM) and two GCMs ECHAM4/OPYC3 and HadCM3 models. The ECHAM4 model predicts a warmer but wetter future climate than HadCM3 for 2020s and 2070s. however, regional variations are shown by both models where both show decreased precipitation in Egypt, Arabian Peninsula and Southern Africa.

The IPCC scientific assessment published a report on Climate Change in 1991. The report analyses various factors affecting the climate of world in future including green house effect and other anthropogenic activities. General Circulation Models (GCMs) are utilized in the report to study these changes. The report suggests an increase in global mean temperature by 1ºC above the present value by 2025 and an increase of about 3ºC by next century. Variation in temperature and precipitation is mostly regional where South Asia sees an increase in precipitation from 5-15% in summer.

Landwehr et al.(2010) studied climate change impacts on reservoir management operations at Coralville dam, Iowa. Soil and Water Assessment Tool (SWAT) was used for hydrologic analysis while North American Regional Climate Change Assessment Program (NARCCAP) dataset provided the required climate data under A2 emission scenario. Two general circulation models were used for the analysis namely CGCM and CCSM. With several limitations of hydrologic and climatic models, the study showed increase in major floods and recommended management strategies for the reservoir.

Garrison Dam in North America was studied for climate change associated sediment yield impact study by US Army Corps of Engineers in 2012. Five different climate scenarios developed by US Bureau of Reclamation were used for the study. The scenarios being wetter and cooler, wetter and warmer, cooler and drier, warmer and drier and median future rainfall and temperatures were studied for two different time periods 2010-2039 and 2040-2069. Variable Infiltration Capacity Model was used and values of different parameters like runoff, infiltration and ground water contribution was calculated. New elevation storage relationships and inflows were developed. The study shows increase in reservoir pool elevation due to increased inflows in future.

Wet areas are going to become wetter and dry areas drier. More precipitation is expected in high altitudes while China, Australia and the Pacific would receive less pour [Dore, 2005].

Bart Nijssen et al. (2001) used four GCMS (HCCPR-CM2, HCCPR-CM3, MPI-ECHAM4, DOE-PCM3) to assess the effect of climate change on nine major continental rivers in US. Macroscale hydrologic model (MHM) was used to calculate changes in hydrologic parameters. The GCMs predicted warmer winters in higher altitudes. Precipitation can be seen increasing though there are major variations regionally. Increased temperatures show increased spring flow in snow packed regions while winter flow are high for transitional regions.

Hydrological response to climate and land use changes of a catchment in Tropical Africa was studied using Precipitation Runoff Modeling System (PRMS) developed by US Geological Survey. Total study period of 11 years was divided into calibration (1986-1990) and validation (1991-95) time periods. According to the simulation, a 10% reduced rainfall would result in 30% less hydrological response while an increase of 1.5°C would decrease the discharge to 15% [Legesse et al., 2003].

A unique approach was used when the effect of global climate change on terrestrial net primary production was studied. A terrestrial ecosystem model (TEM) was used to calculate Net Primary

Production (NPP) for current climate and CO2. The output from General Circulation Models (GCMs) was used to study the effects of projected climate change and CO2 doubling on NPP worldwide [Melillo et al., 1993].

Shi et al. (2006) simulated future climate in North West China for double CO2 concentration using regional climate model RegCM2. Relationship between evaporation and precipitation was developed where runoff and water level rise when precipitation exceeds evaporation. The study concluded annual temperature would increase by 2.7ºC and annual precipitation would increase by 25%. This would result in increase in annual runoff to about 10%.

Chapter 3

DATA AND METHODOLOGY

3.1 STUDY AREA

Rawal dam is located in Pothohar Plateau of Pakistan. Kaurang river is the main river of the reservoir which receives water from 4 major tributaries and 43 minor streams. Some of these streams have perennial flows while some have springs in their beds generally known as Kathas. In addition to Kathas, dry nullahs called Kassis are also found frequently along the tract of Kaurang river [Altaf, 2016]. The study area lies in subtropical part of Pakistan [Champion et al., 1965].

Geographically, the coordinates of Rawal Dam are 73º3'-73º24'E and 33º41'-33º54'N with a watershed of 268km² in Southern Himalayas mountains of Pakistan. The elevation ranges from 523-2145m in the watershed [Ashraf et al., 2014]. Aftab (2010) reported that 47% of catchment area of Rawal Dam lies in Islamabad, 43% is in Punjab while 10% lies in Khyber Pakhtunkhawa.

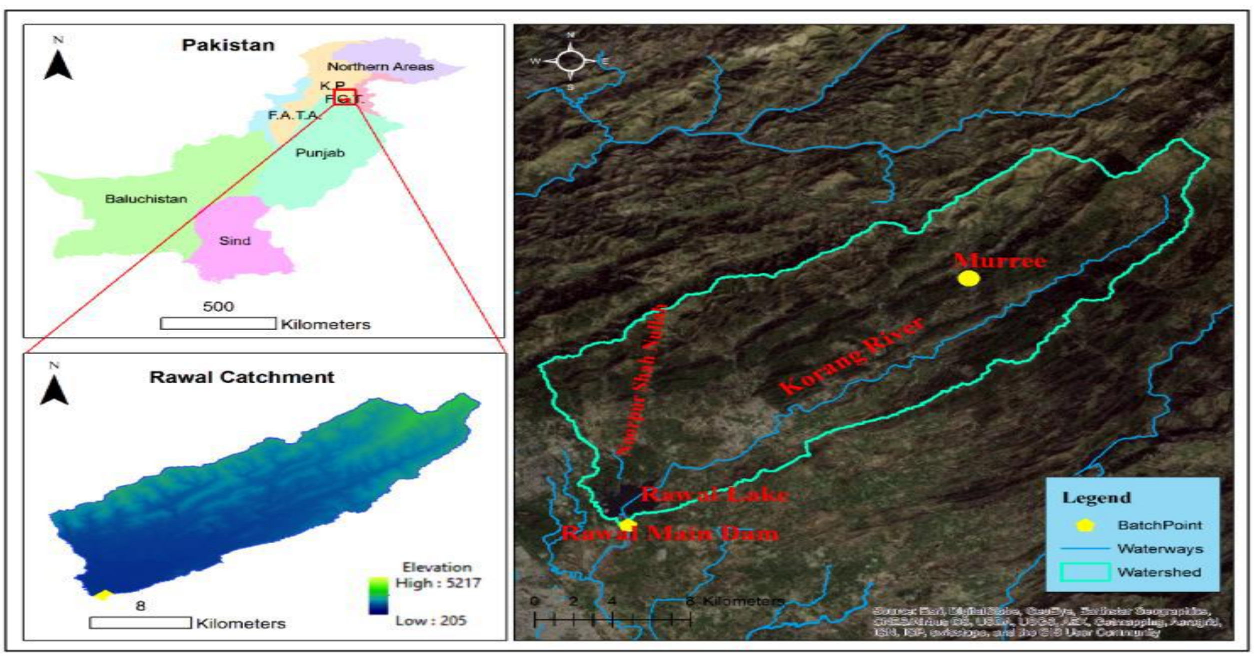

Figure 2: Study Area

Humid sub-tropical climate dominates the study area with mean annual rainfall of about 1220mm. Margalla hills, which form major part of catchment area are subjected to occasional snowfall during winter season i.e., Nov-Feb. June and July see some hottest temperatures with a range of 36-42ºC while December and January are the coldest months with temperature varying from 3ºC to 5.5ºC. Temperature extremes in the area are 48ºC and -4ºC. The catchment receives two rainy seasons. Winter rains occur during Jan-Mar while the area receives fair share of summer rains during July to September usually known as Monsoon period which contributes about 60% of the total rainfall. Rawal Lake alongwith Simli and Khanpur dam regulate the climate of Islamabad [Jadoon et al., 2012].

Rawal dam is one of the main source of water supply to the twin cities of Rawalpindi and Islamabad supplying around 23MGD of water. Water from Rawal Dam is used not only for drinking purposes but also for irrigation of 500 acres command area. Increasing population has put negative stress on this water resource along with evaporation and other losses. Rawal lake covered an area of 594 hectares in 1992 which has now shrunk to 478 hectares. This means that the area covered by lake has shrunk by 19.5% in 2 decades [Butt et al., 2015].

Murree hills are mostly formed of siltstone and sandstone of Murree and Kuldana formations belonging to Oligocene and Miocene age. Sandstone is hard and compact and is red to reddish grey in color. Rocks in Margalla hills are sedimentary and belong to Jurassic to Paleocene age and are composed of Limestone of Samana Suk and Lockhart formation [Ali et al., 2010].

Margalla and Murree hills are characterized by steep slopes and gullies. Alluvial soil dominates the intermountain valleys and vary from silt loam to silty clays. The soil is fine textured and well developed with dark brown to yellowish brown in color and with pH ranges within 5.2 to 8.1 and are susceptible to landslides. Both scrub and coniferous forests are present on the hills which are susceptible to reduction due to excessive urbanization and other human activities leading to flash floods and sedimentation.

Table 3: Salient Features of Rawal Dam

Feature	**Description**
Catchment Area	273km²
Dam Type	Stone Masonry Gravity Dam
Length of Dam	700ft
Spillway Crest Level	R.L 1+742ft
Capacity of Spillway	82000csc
Normal Reservoir Level	R.L 1+752ft
Dead Storage Level	R.L 1+708ft
Top width of dam	14ft
Designed Live Storage Capacity	43000Aft
Dead Storage Capacity	915 Aft
Irrigation System	Gravity flow
G.C.A	550 Acres
C.C.A	500 Acres
Capacity of Irrigation System	40 csc

3.2 DATA SETS

3.2.1 Hydro-Meteorological Data

For precipitation data, two climatic stations were used. Daily data from Murree station was obtained for the time 1974-2014 from Pakistan Meteorological Department (PMD) while for Rawal Dam from Small Dams Organization for the time 1975-2014. Historical records for 1983-2010 has been used as base line period for both stations. Other hydro-meteorological data i.e., elevation-storage curve, daily reservoir pool elevations, daily reservoir inflow, daily spillway discharge and daily discharge through Shahana and Ojri distributaries of Rawal Dam was acquired from the available record of 1992-2014 from Small Dams Organization, the controlling authority of Rawal Dam.

Table 4: Meteorological Stations

Station No.	Station Name and Type	Record Period (Daily)	Elevation	Average Annual Precipitation	Agency
1	Murree/Non-Recording	1983-2010	2260m	1542mm	PMD
2	Rawal Dam/ Non-Recording	1983-2010	528m	1326mm	Small Dams Organization

3.2.2 Remote Sensing Data

Digital Elevation Model of Rawal dam and its water shed with the resolution of 30x30m along with Landsat imageries was obtained from USGS earth explorer for delineation of Rawal Dam catchment and extraction of physical parameters like elevation, slope, catchment area etc.

3.2.3 Climate Projected Data

(HI-AWARE) Himalayan Adaptation, Water and Resilience project has documented reference climate data sets of daily precipitation for Indus, Ganges and Brahmaputra (IGB) river basins. 8 GCM runs have been scrutinized by Lutz et al. from 163 GCM runs obtained from Coupled Model Intercomparison Project, Phase 5 (CMIP5) repository for IGB river basins using a combination of envelope approach and past performance approach. The data sets included are inmcm_rlilp1, CMCC-CMS_rlilp1, bcc-csm1-1_rlilp1, CanESM2_r3ilp1 (RCP8.5) and BNU-ESM_r1ilp1, inmcm4_r1ilp1, CMCC-CMS_rilp1, CSIRO-Mk3-6-0-r4ilp1 (RCP4.5). Downscaled datasets at 5x5 km grid on the basis of Representative Concentration Pathways (RCPs) were obtained to study projected hydrological changes in Rawal Dam catchment.

3.3 PRELIMINARY ANALYSIS

Preliminary analysis of precipitation at Rawal dam and Murree station have been carried out to analyze the available data and to study the trends. Both stations have non-recording rain gauges installed and the records are noted manually by the official staff of CDA and Small Dams Organization. Analysis of historical record of Rawal dam (1975-2014) shows increasing trend of precipitation with the regression equation of $y = 7.2588x - 13373$. The highest amount of precipitation was 1661mm recorded in 1994. However, analysis of Murree Station (1974-2014) show decreasing trend in precipitation over the years with highest recorded precipitation of 2434mm in 1992 and the regression equation of $y = -10.703x + 23122$. Murree station, being on the higher elevation than Rawal Dam receives more precipitation. The analysis of time series of both stations also showed sudden precipitation peaks at Rawal Dam which may cause flash floods in the reservoir while those of Murree station showed gradual increase and later on decrease in precipitation peaks.

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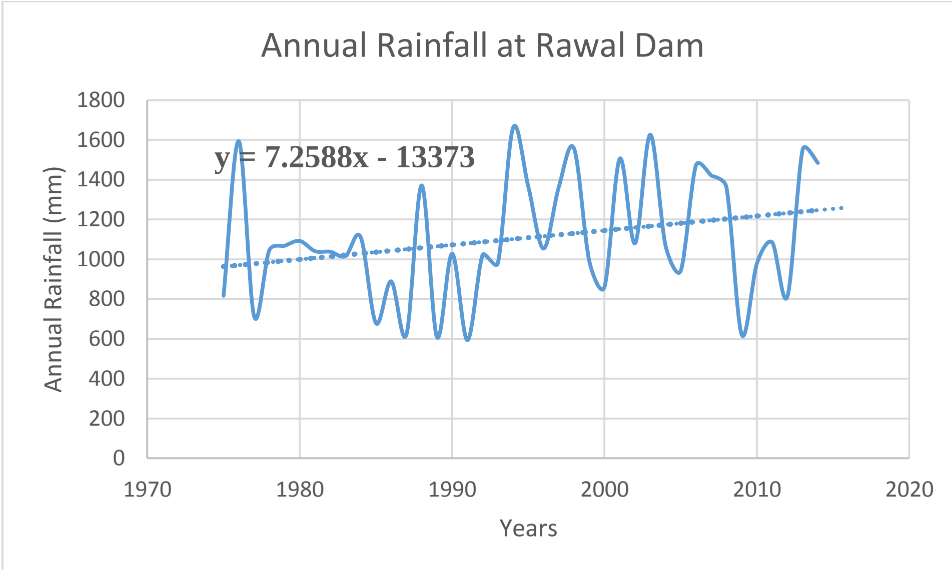


Figure 3: Annual Precipitation at Rawal Dam

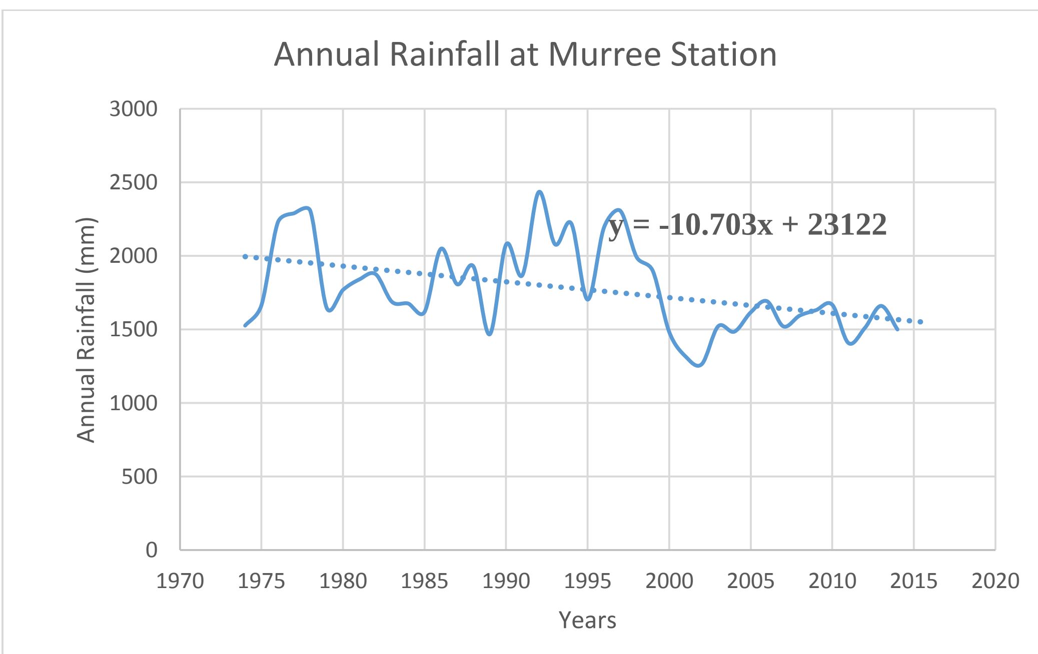
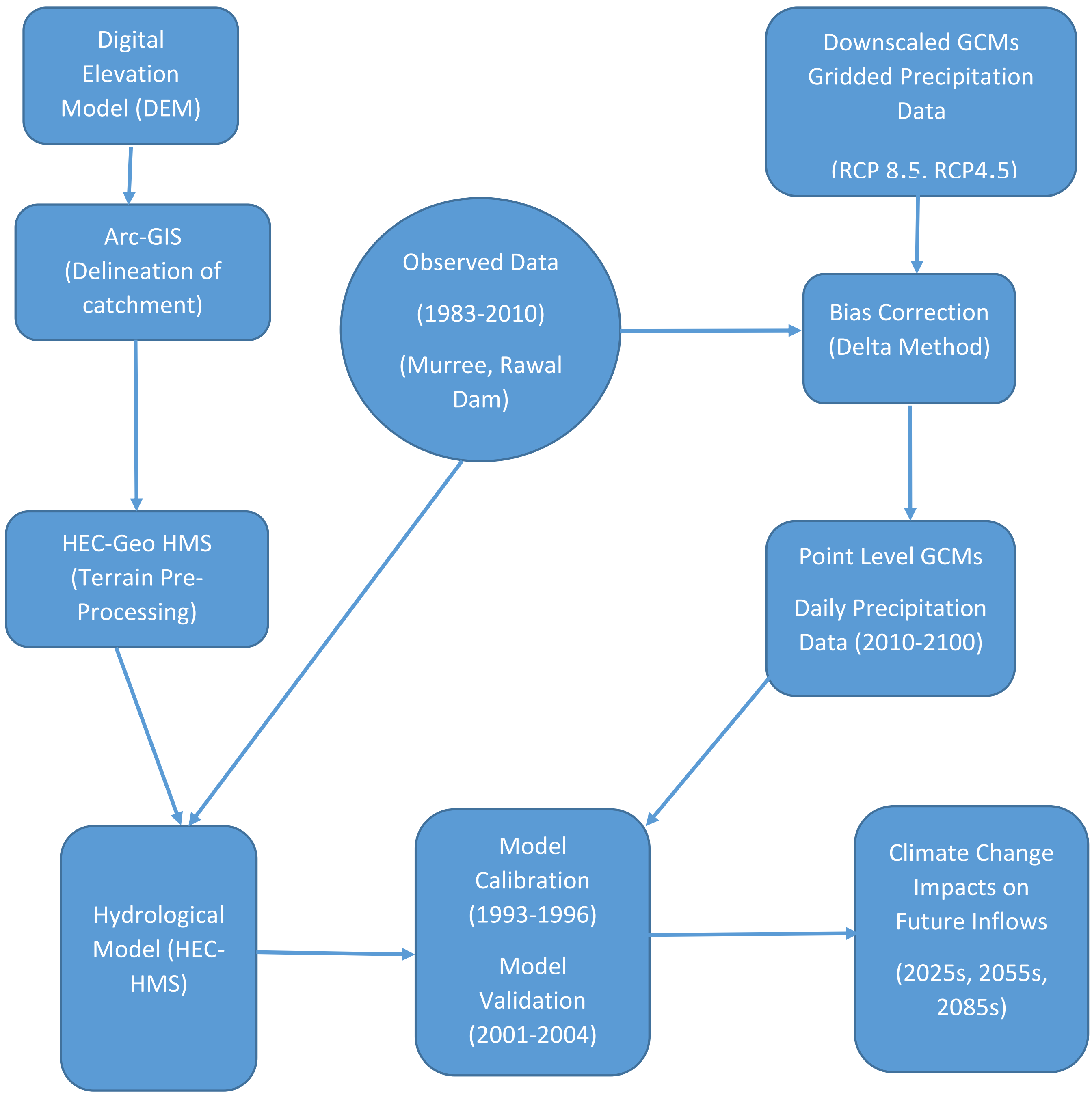


Figure 4: Annual Precipitation at Murree

3.4 METHODOLOGICAL FRAMEWORK



3.5 DIGITIAL ELEVATION MODEL EXTRACTION

Digital Elevation Model (DEM) in the resolution of 30x30m was obtained from USGS Earth explorer. Arc-Map, the desktop of Arc-GIS was then utilized to extract watershed of Rawal Dam and demarcation of Rawal dam from the extracted DEM.

3.6 HYDROLOGICAL MODELING

Pre-processing of delineated watershed was carried out using HEC-GeoHMS, an extension of Arc-GIS to carry out spatial analysis and to extract terrain information. Proper Coordinate System i.e, WGS 43N was assigned to the watershed. Basin parameters e.g., river slope, longest flow path, basin area, stream lines, river length were derived using HEC-Geo HMS in Arc-GIS 10.1. The catchment of Rawal Dam was divided into four sub-basins depending upon the physical characteristics, flow direction, accumulation of flow and availability of gauging stations.

The sub-divided basin was then imported into HEC-HMS for hydrological modeling. Different combinations for loss, transformation and routing methods were applied to see which combination fits best for the model. Daily precipitation data for Rawal Dam and Murree Station was inserted. Elevation-Storage Relationship obtained from hydrological survey conducted at Rawal Dam was also entered. Daily time step was used for precipitation data. Spillway discharge data was inserted as outflow from the reservoir. Model was first calibrated for the years 1993-1996 and the parameters were optimized manually until a good simulation was obtained against the observed data. The same parameters were then utilized for validation of results. The validation period was 2001-04.

3.7 PERFORMANCE INDICATORS

Performance of hydrological model was performed by running three tests; Coefficient of Determination (R^2), Nash-Sutcliffe Coefficient (Ns) and Root Mean Square Error.

3.7.2 Coefficient of Determination (R^2)

It is a statistical parameter which indicates the variation in dependent variable predictable from the independent variable. It is used to check the goodness fit of the model. A model is good fit if the difference between observed values and those predicted by the model is small. R^2 gives a measure of distance of data to the fitted regression line. In other words, it is square of correlation between observed and model predicted values. The value of R^2 ranges from 0-1. 0% indicates that the model failed to explain the variability of data around average. 100% indicates that the model successfully explained all the variability of data around its average. Generally, the closer the R^2 values to 1, the better fit is the model.

Mathematical expression for R^2 is given as:

$$R^2 = \{\frac{\sum[(xi - \bar{x}) * (yi - \bar{y})]}{N * (\sigma x * \sigma y)}\}^2$$

Where:

N is the number of observations, i is the observation and xi and yi are its x and y values respectively. $\bar{x}$ is the average x value while $\bar{y}$ is the average y value. σx is the standard deviation of x while σy is the standard deviation of y.

3.7.3 Nash Sutcliffe Coefficient (Ns)

Nash Sutcliffe is hydrological model efficiency coefficient and its value indicates how good the model prediction is. Its values range from - ∞ to 1. When efficiency E=1, the modeled discharge is the best match to observed values. When E=0, the average of observed values match the accuracy of modeled predictions. When E<1 or a negative value, the predictions of model don't even match with the average of observed values and mean of observed values is a better predictor. The closer the values of Ns to 1, the accurate the model is.

The mathematical expression for Ns coefficient is

$$E = 1 - \frac{\sum (Qo - Qm)^2}{\sum (Qo - \overline{Qo})^2}$$

Where:

Qo is observed discharge values, Qm is modeled values of discharge, $\overline{Qo}$ shows average of observed flows.

3.7.4 Root Mean Square Error (RMSE)

Root Mean Square Error or Deviation is another statistical parameter used to find the difference between modeled values and observed values. It shows the standard deviation of difference between observed data and corresponding predicted/modeled values. It is a simple method to test the accuracy of model predictions and to check predicted errors of different models. It aggregates the magnitude of errors in modeled values for various calculations into a single measure of predictive power. This parameter is sensitive to outliers.

Mathematical expression for RMSE is

$$RMSE = \sqrt{\frac{\sum_{n}^{i=1} (xo,i - xm,i)^2}{n}}$$

Where:

Xo is observed ith value, xm is corresponding modeled ith value, n is the total number of observations.

3.8 CLIMATE DATA SETS AND BIAS CORRECTION

Coupled Model Intercomparison Project (CMIP) was established by World Climate Research Program to develop standard protocols for using General Circulation Models (GCMs) in the development of emission scenarios. Climate Modelers from all over the world developed CMIP to develop a set of protocols to study the output of coupled atmosphere-ocean general circulation models (AOGCMs). 5th phase of CMIP i.e., CMIP5 contains 94 GCM runs forRCP4.5 and 69 runs forRCP8.5 in its repository.

The output from GCMs is usually directly downscaled from coarse spatial resolution to higher resolution for regional climate models (RCMs). Those downscaled results are later on utilized for assessment of future climate change or to run models for studying climate change impact. Climate change impact studies cannot accommodate all projections due to availability of numerous models and computational/human resource incapacity. Hence, one climate model or a small ensemble of some climate models is used for studies. The selection of climate model depends on multiple factors. Two approaches are used for selection of climate models.

1. Past-Performance Approach: here, the model is selected on the basis of its ability to simulate present and near-past climatic conditions.
2. Envelope Approach: Here, an ensemble of models is considered which cover a relatively high range of projections for one or more variables of interest (Lutz et al., 2016)

Both of these approaches have been used in this study to select climate data set for climate hot spot i.e., Indus, Ganges and Brahamaputra river basins. RCP4.5 andRCP8.5 model runs have been used. Initial selection of model is based on projected average annual change in precipitation sum. The selection was refined on the basis of changes in precipitation extremes. Final selection was based on past performance validation of model. Selected RCPs represent one medium stabilization scenario and one high emission scenario.

After the selection process, the final ensemble of GCMs is composed of 8 GCM models; four for RCP8.5 and four for RCP 4.5. Daily precipitation data for the coordinates of Rawal Dam and Murree station was extracted using programming language package R.

Bias correction of extracted RCM data sets was done by applying a correction factor on referenced and future data sets. It is important since the raw climate models may contain certain biases due to systematic errors, lack of knowledge of climatic processes or simplified physical processes.

For bias correction (BC), monthly average and standard deviation for historical referenced data of precipitation from the model and observations (1975-2014). The correction factor was then determined for both average and variation using the following equations:

$$Vc=\frac{\overline{Vobs}}{\overline{Vref}}$$

$$Sc=\frac{\sigma obs}{\sigma ref}$$

Here,

V_c= correction factor for average

S_c= correction factor for standard deviation

$\overline{Vobs}$= average of observed values

$\overline{Vref}$= average of model referenced data

σobs= standard deviation of observed data

σref=standard deviation of model referenced data

The calculated correction factors were then used to obtain bias corrected projected climate parameter V'_{proj}.

$V'_{proj} = (V_{proj}-\overline{Vref}).Sc+(\overline{Vref}.Vc)$

The above mentioned procedure was adopted for bias correction of historical referenced and future data sets. Moreover, the model discrepancies were assumed to remain constant in time.

3.9 FUTURE WATER AVAILABILIITY AND CLIMATE CHANGE

The downscaled daily precipitation data of RCPs were adopted after careful bias correction of the climate datasets by employing delta bias correction technique to study the projected changes in in hydrological regime of the study area. The observed hydro-climatic and IGB climatic data sets for period of 1983-2010 were used as reference precipitation hereafter referred as baseline (observed) and baseline (GCM) for future decadal climate i.e.,

2025s (2010-2040)

2055s (2041-2070) and

2085s (2071-2100).

The projected changes in decadal (2025s, 2055s and 2085s) precipitation variable both for RCP8.5 and RCP4.5 were assessed in comparison with the baseline (observed) climatic data set. Subsequently, the corrected decadal climatic dataset were utilized as an input in hydrological model to project the scenarios. Further the projected changes in potential storage of the Rawal Dam catchment were assessed in comparison with baseline (observed) stream flow. The aforementioned changes in precipitation and inflows were assessed by taking average of four GCMs belonging to each of RCP8.5 and RCP4.5. To carry out the aforementioned assessments, the well calibrated and validated HEC-HMS model was used. The ground stations of Rawal dam and Murree were simply replaced with daily bias corrected precipitation data acquired after extraction of the same from climatic dataset of 8 GCM models provided by HI-AWARE. The decadal values of potential storage were recorded for further analysis and forecasting.

Chapter 4

RESULTS AND DISCUSSIONS

4.1 HYDROLOGICAL MODELING

Twelve different combinations of methods available in HEC-HMS were tried for simulation of historical hydrological response of Rawal dam to precipitation. It was found out that bounded recession base flow method yields poor results. Constant monthly baseflow method and recession method proved to be good for simulation. Similarly, in loss method, SCS loss gives highly exaggerated values however, Initial & Constant and Deficit & Constant Loss Method give satisfactory results. After numerous trials and errors, the set of methods found suitable for this study comprised of Recession method for baseflow computation, Deficit and Constant for losses calculation, Clark Unit Hydrograph for transformation and Muskingum method for routing.

Table 5: Parametric values of HEC-HMS for simulation

Sub-Basin	Initial Deficit (mm)	Max Storage (mm)	Constant Rate (mm/hr)	Impervious (%)	Time of Concentration (hr)	Storage Coefficient (hr)	Recession Constant
W1	15	30	2.3	3	3	9	0.89
W2	15	30	2.2	3	3	9	0.89
W3	15	30	1.8	4	2.5	6	0.89
W4	15	30	1.9	4	2.5	6	0.89

Fig 6 and 7 show simulated and observed reservoir levels for the period of calibration and validation. It is clear from the figure that the model has simulated the historical hydrological response satisfactorily. All high reservoir levels have been catered by the model. Except a few exaggerated results, like for the year 1992 in calibration, HEC-HMS has successfully simulated the reservoir levels.

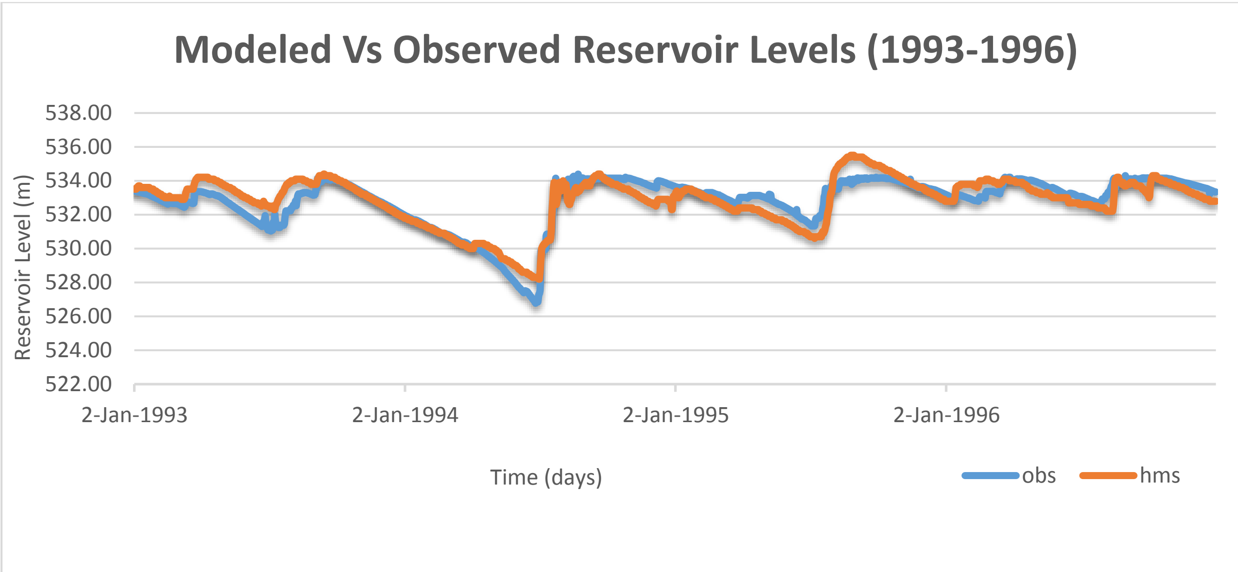


Figure 5: Simulated and Observed Reservoir Levels for Calibration Period

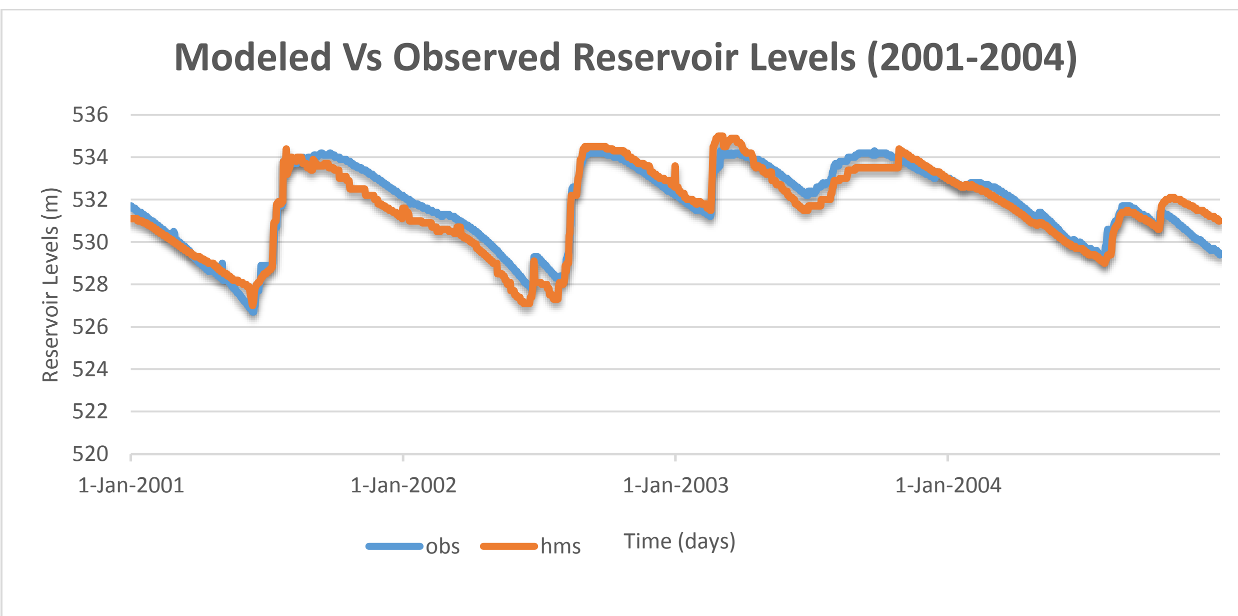


Figure 6: Simulated and Observed Reservoir Levels for Validation Period

Statistical parameters used to check performance of calibrated and validated model are Nash-Sutcliffe coefficient, Root Mean Square Error and Coefficient of Determination. Table 6 presents performance indicators of developed hydrological model for calibration and validation on seasonal basis. These indicators show that the model performed differently for calibrated and validated time periods. For calibration, the performance of model was very good in Spring and Summer. The values of Nash-Sutcliffe Coefficient of 0.84 and 0.83 depict good simulation however with R^2 value of 0.544 and Nash-Sutcliffe coefficient of 0.35 the model did not simulate Monsoon fairly. For validation, the model yielded good results in summer and Monsoon. The values of Nash-Sutcliffe Coefficient of 0.94 and 0.92, R.M.S.E of 0.55 and 0.53 and R^2 of 0.95 and 0.96 show quite good performance of the model. This shows that inflows changed during calibration and validation periods and so did the hydrological response of the catchment. High flows of Monsoon and fair winter rains have also been catered well by the model. Performance of model during autumn has been satisfactory.

Table 6: Seasonal Performance Indicators

Season	Nash-Sutcliffe Coefficient (Ns)		R.M.S.E		Coefficient of Determination (R^2)	
	Calibration	Validation	Calibration	Validation	Calibration	Validation
Winter (Nov-Feb)	0.61	0.97	0.49	0.74	0.661	0.619
Spring (Mar-Apr)	0.84	0.93	0.57	0.49	0.8563	0.949
Summer (May-June)	0.83	0.94	0.89	0.55	0.8484	0.954
Monsoon (July-Aug)	0.35	0.92	1	0.53	0.5445	0.960
Autumn (Sep-Oct)	0.49	0.79	0.41	0.57	0.1054	0.82
Annual	0.78	0.898	0.7	0.61	0.7853	0.907

4.2 CLIMATE CHANGE PROJECTIONS

4.2.1.1 Bias Correction

Climate dataset of 8 GCM models downscaled at 5kmx5km grid for Rawal Dam and Murree was selected for studying impacts of future climate on the reservoir. Baseline period of 1983-2010 was selected. Dataset for precipitation was extracted for Murree and Rawal Dam for the same period from the IGB data set and was then compared with observed precipitation data of both stations to observe uncertainties. Extracted precipitation data was found to be quite uncertain therefore delta technique of Bias Correction was applied to it which removed the uncertainties. The corrected precipitation data was then used for future climatic impact studies. The same is depicted through figures 7 and 8 where a comparison chart has been shown to describe the corrected data set values.

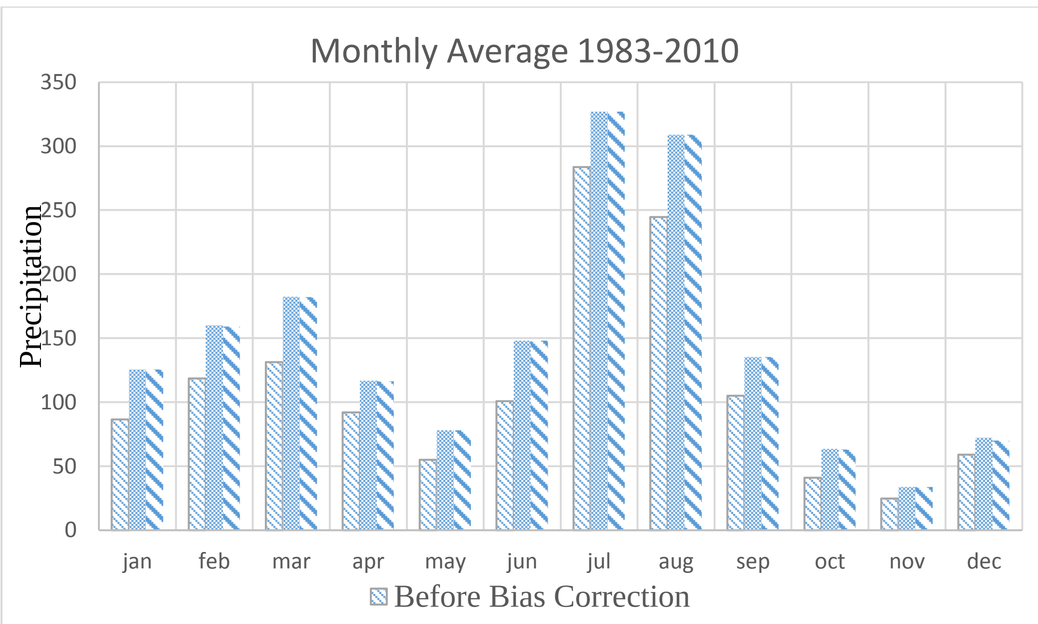


Figure 7: Bias Correction Murree Station

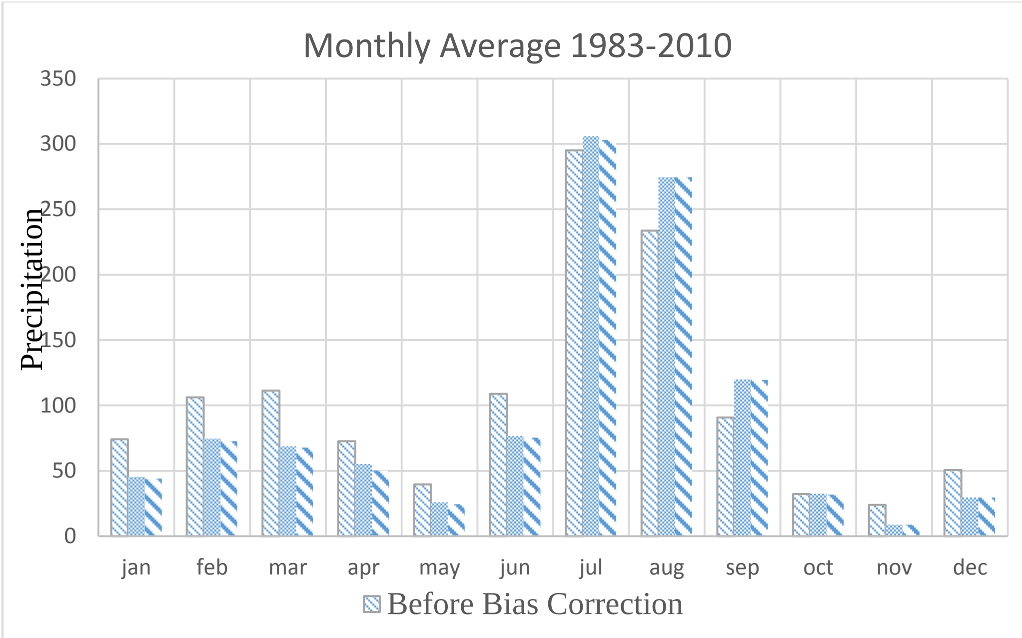


Figure 8: Bias Correction for Rawal Dam

4.2.1.1.1 Projections of Precipitation under Climate Change

Murree Station

Figure 9, 10 and 11 show future projection of precipitation at Murree climate station from current climate to end of the century under Representative Concentration Pathways 8.5. Baseline time period for current climate representation is 1983-2010. Looking at the graphs, it is clear that average of RCP8.5 models follow the trend of baseline period with a positive shift in future precipitation with a major increase in Feb-Apr and in Monsoon period. Individually, Can-ESM_85 continuously shows increase in precipitation throughout the century. Inmcm4_rcp85_r1i1p1 shows less than average precipitation for 2025s while for the rest of the century, it predicts higher than average precipitation with constantly high Monsoon flows during 2055s and a highest precipitation peak in July of 2085s. BCC-CMS_85 show highest flows during 2025s and 2055s with a highest peak in Sep of 2055s. For 2085s, it gives higher than average Monsoon flows. CMCC-CMS_rcp85_r1i1p1 shows the lowest flows throughout the century and for 2085s, it is even less than baseline precipitation. Referring to Table 7, average of 4 models of RCP8.5 shows increase in winter precipitation at Murree Station throughout the current century with 12.81mm, 2.01mm and 7.79mm above the baseline data. Spring season shows increase during 2025s with the value of 3.36mm above the baseline data however, in 2055s and 2085s it predicts decrease in precipitation with the values of -62.67mm and -79.68mm respectively. Summers too are going to receive lesser pour while Monsoon receives heavy rainfall throughout with the values of 30.91mm, 93.89mm, 56.43mm more than historical referenced data. Autumn too would receive more precipitation according to the analysis. On the average, Murree station is going to receive 104.4mm during 2025s, 4078mm during 2055s and 160.25 during 2085s more than the baseline precipitation according to RCP8.5 emission scenario.

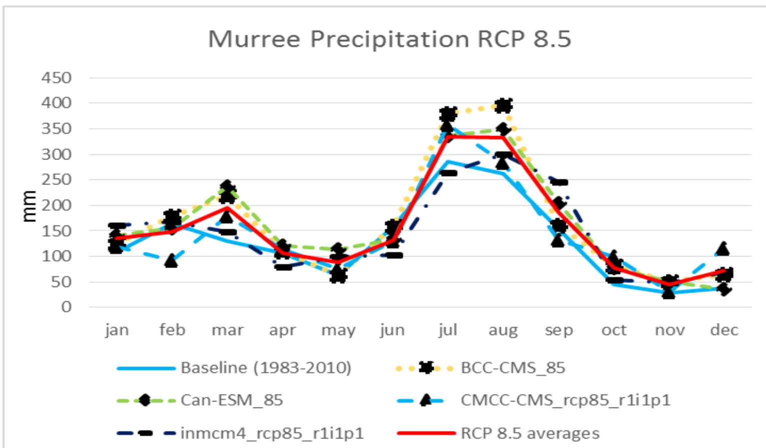


Figure 9: Murree Precipitation RCP8.5 (2025s)

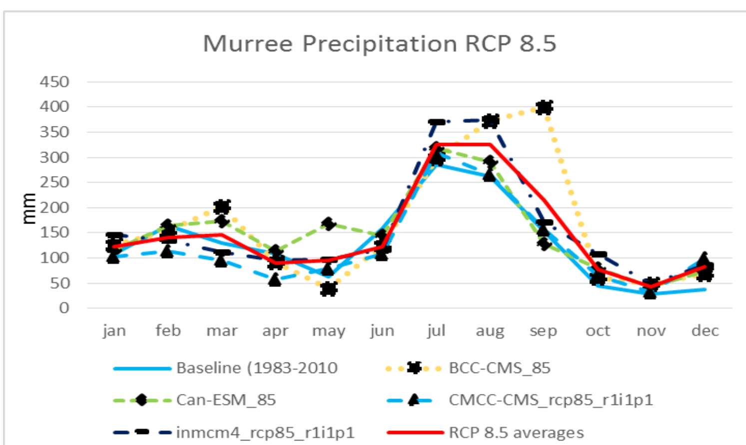


Figure 10: Murree Precipitation RCP8.5 (2055s)

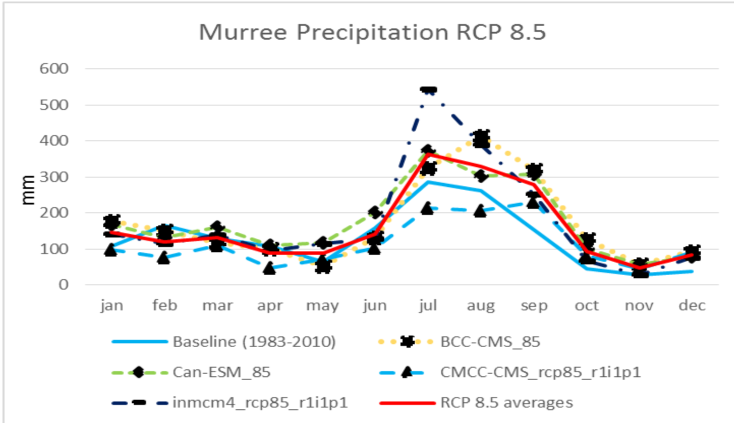


Figure 11: Murree Precipitation RCP8.5 (2085s)

Fig 12, 13 and 14 show future projection of precipitation at Murree Climate Station from current climate to end of the century underRCP4.5. From the graphs, it appears that average ofRCP4.5 models follow the trend of baseline precipitation positively and higher precipitation in Monsoon. Individually, CSIRP-Mk3-6-0_rcp45_r4i1p1 give less that average precipitation in 2025s while for 2055s and 2085s, precipitation appears to be increasing with highest peak in Aug of 2055s and increased winter and Monsoon rainfall. INMCM_45 gives near to average values throughout the century. BNU-ESM_45 show highest precipitation peak during spring, summer, monsoon of 2025s and 2085s while for 2055s, it shows near to average precipitation. CMCC-CMS_rcp45_r1i1p1 gives high values of precipitation during monsoon throughout the century. Referring to Table 7 again, Murree station under RCP4.5 is going to receive heaviest pours during Autumn with the values of 135.31mm during 2025s, 66.44mm during 2055s and 147.11mm during 2085s more than the base line precipitation. 2nd highest increase in precipitation is going to be observed in Monsoon with 23.07mm, 24.6mm and 24.56mm for 2025s, 2055s and 2085s respectively. Winter rains too are predicted to increase with 20.17mm, 37.31mm and 35.27mm during 2025s, 2055s and 2085s respectively above their value in baseline data. On the average, annual increase in precipitation at Murree station under emission scenario 4.5 is 181.61mm, 75.5mm and 155.08mm during the three decadal time slices in order.

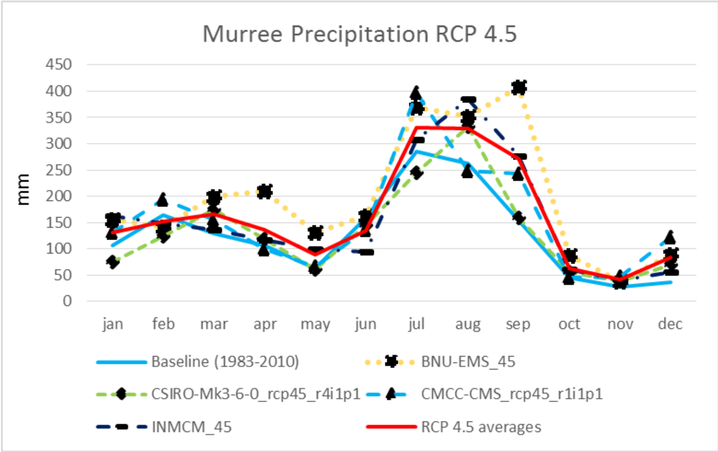


Figure 12: Murree Precipitation RCP4.5 (2025s)

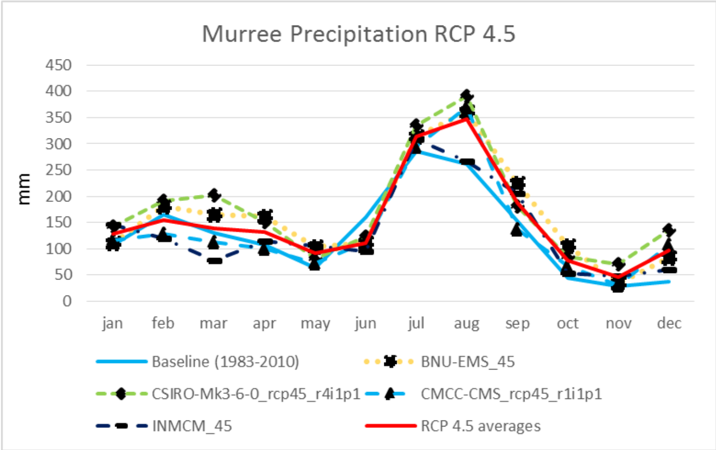


Figure 13: Murree Precipitation RCP4.5 (2055s)

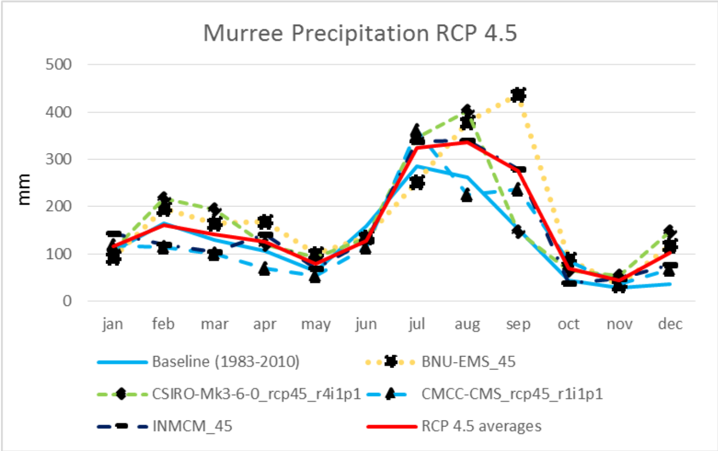


Figure 14: Murree Precipitation RCP4.5 (2085s)

Table 6: Future Projection of Precipitation at Murree Station

	Season/Duration	Murree Precipitation (mm)			
		RCP 8.5		RCP4.5	
		Absolute	Deviation	Absolute	Deviation
2011-2040 (2025s)	Winter(Nov-Feb)	401.05	12.81	408.41	20.17
	Spring(Mar-Apr)	301.60	3.36	302.97	4.74
	Summer(May-June)	218.89	-7.14	224.36	-1.67
	Monsoon(July-Aug)	666.85	30.91	659.00	23.07
	Autumn(Sep-Oct)	262.90	64.49	333.71	135.31
	Annual (Average)	1851.29	104.43	1928.46	181.61
2041-2070 (2055s)	Winter(Nov-Feb)	390.25	2.01	425.56	37.31
	Spring(Mar-Apr)	235.57	-62.67	270.47	-27.76
	Summer(May-June)	219.35	-6.68	200.93	-25.10
	Monsoon(July-Aug)	650.17	14.23	660.54	24.60
	Autumn(Sep-Oct)	292.30	93.89	264.85	66.44
	Annual (Average)	1787.64	40.78	1822.35	75.50
2071-2100 (2085s)	Winter(Nov-Feb)	396.03	7.79	423.51	35.27
	Spring(Mar-Apr)	218.56	-79.68	265.88	-32.36
	Summer(May-June)	229.91	3.88	206.54	-19.50
	Monsoon(July-Aug)	692.37	56.43	660.50	24.56
	Autumn(Sep-Oct)	370.23	171.83	345.52	147.11
	Annual (Average)	1907.10	160.25	1901.93	155.08

Baseline (1983-2010)	Murree Precipitation (mm)
Winter (Nov-Feb)	388.2421
Spring (Mar-Apr)	298.2375
Summer (May-June)	226.0307
Monsoon (July-Aug)	635.9386
Autumn (Sep-Oct)	198.4046
Annual	1746.854

Rawal Dam

Fig 15, 16 and 17 show future projection of precipitation at Rawal Dam station from current climate to end of the century under RCP8.5. Average of RCP8.5 follows the trend of baseline precipitation. CanESM2_rcp85_r3i1p1 gives slightly higher rainfall in Aug of 2025s while it gives lower than average values of precipitation in 2055s and 2085s. Inmcm4_rcp85-r1i1p1 show lower than average value in 2025s while for 2055s and 2085s, it gives highest rainfall peaks during July. Bcc-csm1-1-rcp85_r1i1p give very high values of precipitation for Monsoon of 2025s and 2055s while it shows near to average results for 2085s. CMCC-CMS_rcp85_r1i1p1 show the lowest of all model precipitation throughout the century. Table 8 shows the seasonal analysis of precipitation at Rawal Dam during the current century. Under RCP8.5, highest pour in going to be received in autumn with the values of 63.06mm, 29.53mm and 59.62mm above the referenced period during 2025s, 2055s and 2085s respectively. Summer in 2085s shows 149.61mm increased precipitation while Spring season would see a decrease in rainfall during 2055s and 2085s with the values of -15.65mm and -37.71mm. on average, Rawal Dam under emission scenario RCP8.5 would receive 135.95mm, 110.41mm and 195.78mm more rainfall annually during the decadal time slices in order.

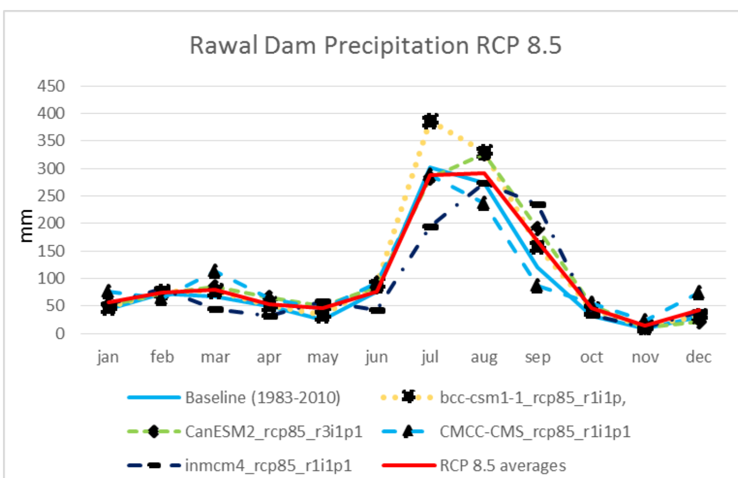


Figure 15: Rawal Dam Precipitation RCP8.5 (2025s)

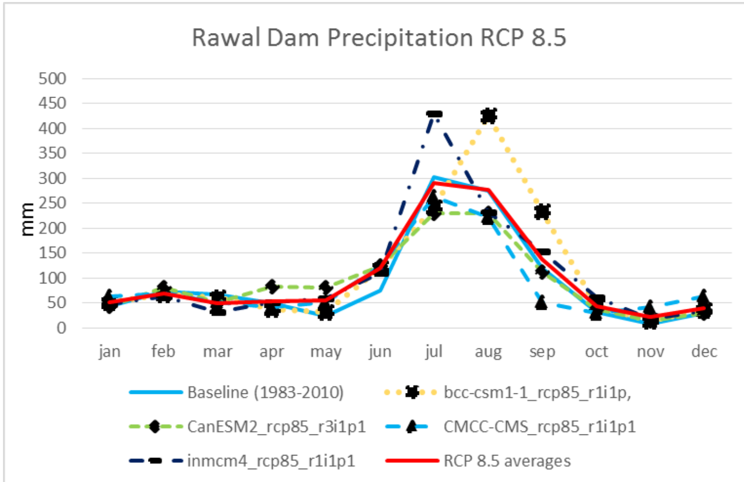


Figure 16: Rawal Dam Precipitation RCP8.5 (2055s)

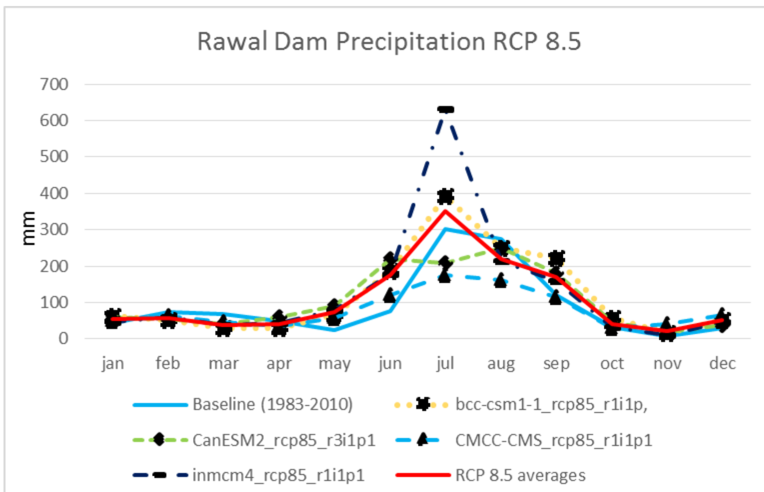


Figure 17: Rawal Dam Precipitation RCP8.5 (2085s)

Fig 18, 19 and 20 show future projections of precipitation at Rawal Dam for a century under RCP4.5. Average ofRCP4.5 follows the same trend and gives almost the same values as for baseline precipitation. CSIRO-Mk3-6-0-rcp45-r41i1p1 shows very low precipitation during 2025s while somewhat higher Monsoon values during 2055s and 2085s. INMCM_45 show near to average values in 2025s while gives very low values during rest of the century. BNU-EMS_45 gives the highest precipitation of all models during Monsoon. CMCC-CMS-rcp45_r1i1p1, too, give high Monsoon peaks throughout the century.

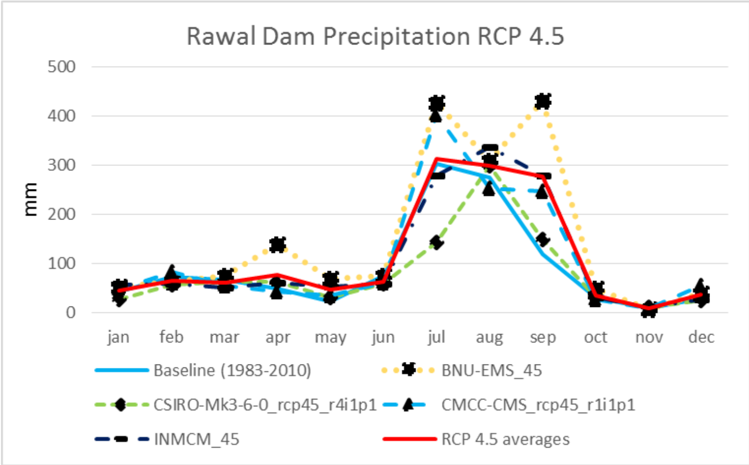


Figure 18: Rawal Dam Precipitation RCP4.5 (2025s)

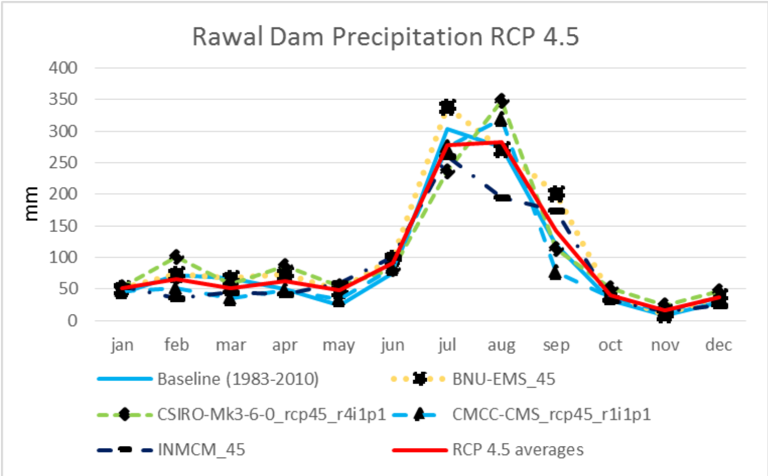


Figure 19: Rawal Dam Precipitation RCP4.5 (2055s)

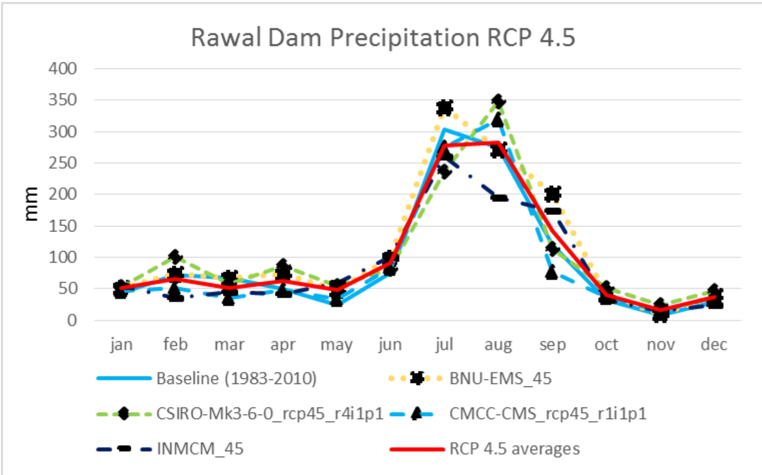


Figure 20: Rawal Dam Precipitation RCP4.5 (2085s)

Referring to Table 8 again, Rawal Dam under RCP4.5 is going to receive heaviest pour druing 160.64mm, 30.25mm and 40.61mm more than baseline precipitation during 2025s, 2055s and 2085s respectively. Monsoon would see increased pour with the value of +34.4mm during 2025s however, during rest of the century, Monsoon would receive lesser rain with the values of -16.8mm and -62.91mm for 2055s and 2085s. The same trend has been observed for Spring throughout the century. Summer would receive high rainfall with the values of +11.31mm, +40.28mm and +121.61mm for the three decades in respective order. On the average, Rawal Dam under RCP4.5 would receive annually increased precipitation with the values of 230.55mm, 63.45mm an d 93.55mm more than baseline pour.

Table 9 shows basin wide precipitation during the current century. Spring season during 2025s is going to receive increased precipitation under RCP8.5 and RCP4.5 with the values of 9.26mm and 12.46mm more than baseline pour. However, both emission scenarios show decreased Spring pour during the rest of the century. Winter rains would be on increasing side with the values of 22.6mm, 15.82mm and 21.66mm for the three decadal time slices in their respective order for RCP8.5 while for RCP4.5 the value turn out to be 12.08mm, 25.39mm and 24.2mm more than baseline data. Monsoon, under RCP8.5 shows increased rainfall with the values of 16.51mm, 8.96mm and 24.35mm for 2025s, 2055s and 2085s respectively while for RCP4.5, 28.89mm and 3.34mm increased values are shown for 2025s and 2055s while during 2085s -20.36mm pour would be received. On average, basin wide precipitation would increase annually with the values of 120.62mm, 76.45mm and 178.5mm under RCP8.5 for the three decadal timeslices in respective order. For RCP4.5 the same values turn out to be 206.74mm, 69.31mm and 123.48mm respectively.

Generally, it has been observed that instead of individual results, average of RCPs gives better understanding of future projections.

Table 7: Future Projection of Precipitation at Rawal Dam

	Season/Duration	Rawal Dam Precipitation (mm)			
		RCP 8.5		RCP4.5	
		Absolute	Deviation	Absolute	Deviation
2011-2040 (2025s)	Winter(Nov-Feb)	187.03	31.88	159.57	4.42
	Spring(Mar-Apr)	133.04	14.86	137.95	19.77
	Summer(May-June)	123.03	23.03	111.06	11.31
	Monsoon(July-Aug)	580.32	2.87	611.85	34.4
	Autumn(Sep-Oct)	214.42	63.06	312	160.64
	Annual (Average)	1237.84	135.95	1332.44	230.55
2041-2070 (2055s)	Winter(Nov-Feb)	184.05	28.9	169.25	14.1
	Spring(Mar-Apr)	102.53	-15.65	113.8	-4.38
	Summer(May-June)	175.74	75.99	140.03	40.28
	Monsoon(July-Aug)	581.41	3.96	560.65	-16.8
	Autumn(Sep-Oct)	180.89	29.53	181.61	30.25
	Annual (Average)	1212.13	110.41	1165.34	63.45
2071-2100 (2085s)	Winter(Nov-Feb)	189.95	34.8	168.87	13.72
	Spring(Mar-Apr)	80.47	-37.71	98.55	-19.63
	Summer(May-June)	248.91	149.16	221.51	121.76
	Monsoon(July-Aug)	571.42	-6.03	514.54	-62.91
	Autumn(Sep-Oct)	210.98	59.62	191.97	40.61
	Annual (Average)	1297.67	195.78	1195.44	93.55

Baseline (1983-2010)	Rawal Dam Precipitation (mm)
Winter (Nov-Feb)	155.15
Spring (Mar-Apr)	118.18
Summer (May-June)	99.75
Monsoon (July-Aug)	577.45
Autumn (Sep-Oct)	151.36
Annual	1101.89

Table 8: Basin wide Projection of Future Precipitation

	Season/Duration	Basin wide Precipitation (mm)			
		RCP 8.5		RCP4.5	
		Absolute	Deviation	Abs	Deviation
2011-2040 (2025s)	Winter(Nov-Feb)	291.15	22.60	280.63	12.08
	Spring(Mar-Apr)	215.04	9.26	218.23	12.46
	Summer(May-June)	169.67	8.48	166.18	5.00
	Monsoon(July-Aug)	622.42	16.51	634.79	28.89
	Autumn(Sep-Oct)	238.00	63.76	322.56	148.32
	Annual (Average)	1536.27	120.62	1622.39	206.74
2041-2070 (2055s)	Winter(Nov-Feb)	284.36	15.82	293.94	25.39
	Spring(Mar-Apr)	167.25	-38.52	190.02	-15.76
	Summer(May-June)	196.96	35.77	169.66	8.47
	Monsoon(July-Aug)	614.86	8.96	609.25	3.34
	Autumn(Sep-Oct)	235.09	60.84	222.10	47.86
	Annual (Average)	1492.10	76.45	1484.97	69.31
2071-2100 (2085s)	Winter(Nov-Feb)	290.21	21.66	292.75	24.20
	Spring(Mar-Apr)	147.65	-58.13	179.95	-25.82
	Summer(May-June)	239.67	78.48	214.23	53.04
	Monsoon(July-Aug)	630.26	24.35	585.54	-20.36
	Autumn(Sep-Oct)	288.45	114.21	266.67	92.42
	Annual (Average)	1594.15	178.50	1539.14	123.48

Baseline (1983-2010)	Basin wide Precipitation (mm)
Winter (Nov-Feb)	268.5452
Spring (Mar-Apr)	205.7748
Summer (May-June)	161.1833
Monsoon (July-Aug)	605.9037
Autumn (Sep-Oct)	174.2464
Annual	1415.653

4.2.2 IMPACTS OF CLIMATE CHANGE ON FUTURE WATER AVAILABILITY

Fig 21, 22 and 23 show potential storage at Rawal Dam under RCP8.5 for this century simulated by the developed model using HEC-HMS. Baseline data available was from 1992-2013. The average of RCP8.5 for inflows follows the same trend as of baseline data. Table 10 shows the values of potential storage at Rawal dam during the current century. Looking at the table reveals that Monsoon would see maximum potential of storage (14%, 9% and 22% more than baseline data) during the three decadal times slices in their respective order. Autumn, too is going to cater more storage with the values of -0.3%, 4% and 22% more than baseline data however a negative values of -0.3% shows decrease in storage during 2025s. On average, Rawal Dam under RCP8.5 would receive waters 26%, 14% and 52% more than baseline data during 2025s, 2055s and 2085s respectively. Can-ESM_85 gives storage almost equal to average of RCP8.5 however, peak of potential storage shifts from July to Sep as we move towards the end of the century. INMCM_85 give much lower values during 2025s, slightly greater in 2055s while much higher values near the end of the century. BCC-CMS_85 give low flows in 2025s, high in middle of the century while medium flows towards the end of the century. CMCC-CMS_rcp85_r1i1p1 continues to give very low storage throughout the century.

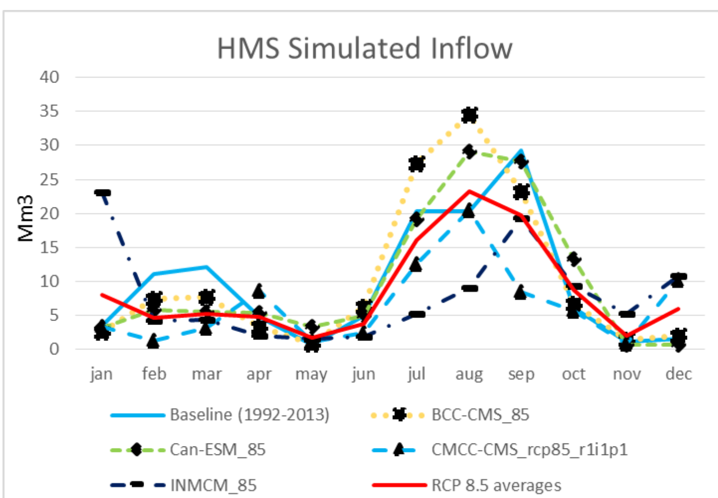


Figure 21: Potential Storage at Rawal Dam under RCP8.5 (2025s)

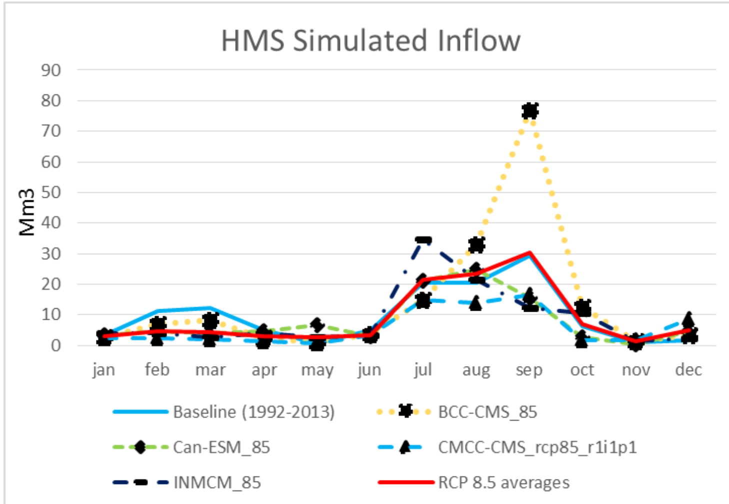


Figure 22: Potential Storage at Rawal Dam under RCP8.5 (2055s)

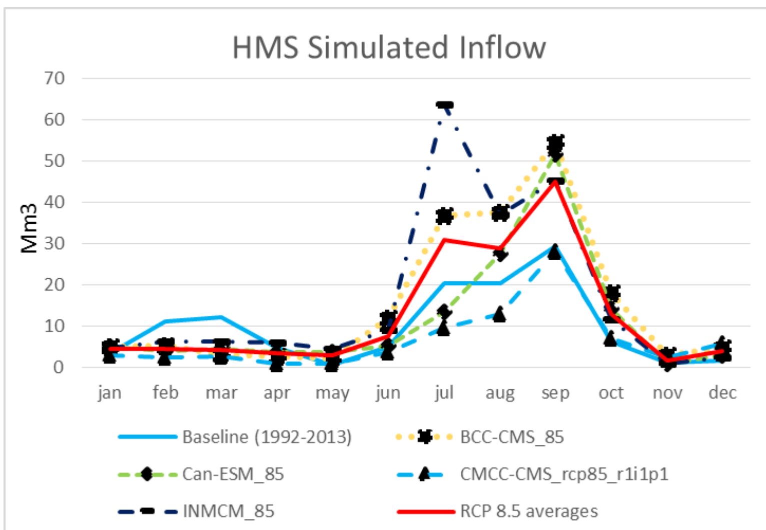


Figure 23: Potential Storage at Rawal Dam under RCP8.5 (2085s)

Fig 24, 25 and 26 depict the projected inflows at Rawal Dam till the end of century under RCP4.5. average ofRCP4.5 follows the trend line of baseline flows but with much lesser values. Table 10 shows that maximum potential of storage in seen in Monsoon and Autumn. In Monsoon, the values are 16%, 9% and 23% more than the baseline values for 2025s, 2055s and 2085s. In Autumn, the storage comes out to be 28%, 0.03% and 17% more then baseline data for the three decadal time slices in their respective order. Least potential of storage is observed in Spring with the value of 1%, -0.7% and 1% more than baseline data. On average, Rawal Dam under RCP4.5 shows an increase in potential storage with the values of (56%, 11% and 45%) for 2025s, 2055s and 2085s respectively. CSIRO-Mk3-6-0-rcp45-r41i1p1 shows very low inflows during 2025s while higher Monsoon values during 2055s and 2085s. INMCM_45 and BNU-EMS_45 show very high flow peaks in the start of century, assumes medium values during the middle while again attains high flows towards the end of the century. CMCC-CMS-rcp45_r1i1p1 follows near to average pattern during 2025s while medium flows during the rest of the century.

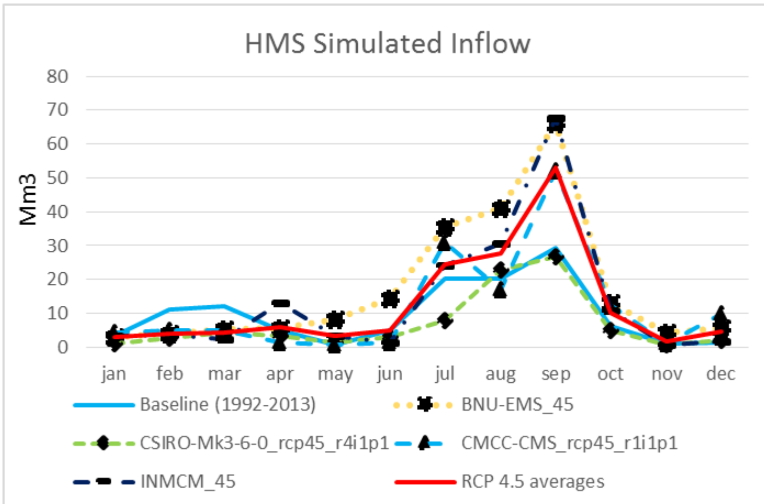


Figure 24: Potential Storage at Rawal Dam under RCP 4.5 (2025s)

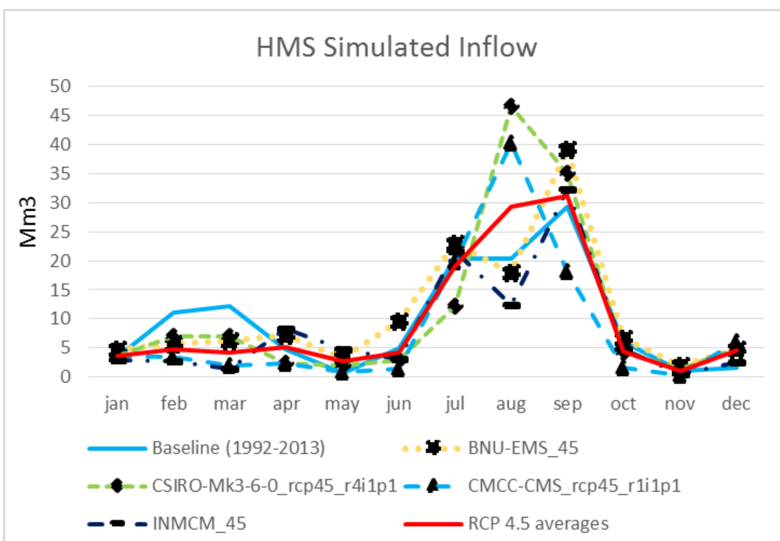


Figure 25: Potential Storage at Rawal Dam under RCP 4.5 (2055s)

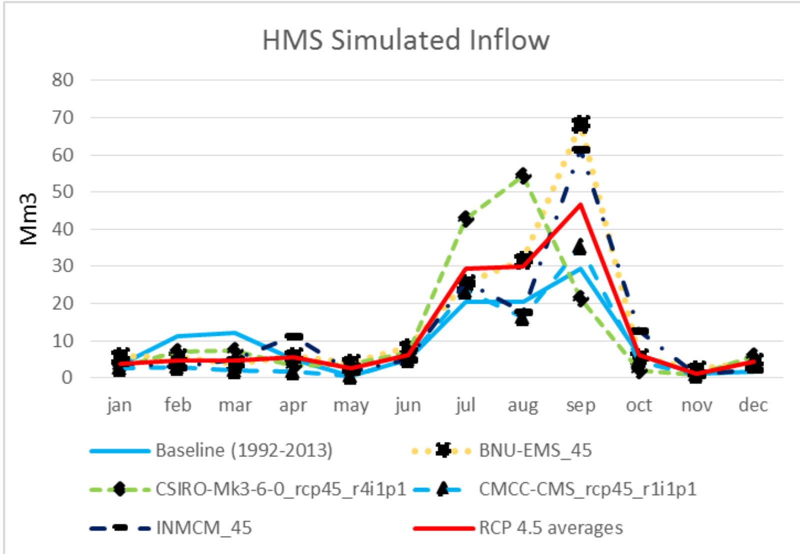


Figure 26: Potential Storage at Rawal Dam under RCP 4.5 (2085s)

Generally, climate change projections shows two clear peaks of both precipitation and inflows; one during winter rains and the other during Monsoon. For Rawal Dam, RCP8.5 show much higher values of anticipated precipitation than RCP4.5. Moreover, the values of projected precipitation exceed the baseline historical record. The same trend can be seen for potential storage where RCP8.5 projects higher values than those projected by RCP4.5.

Table 9: Future Projection of Potential Storage at Rawal Dam

	Season/Duration	Potential Storage available at Rawal Dam (Mm³)			
		RCP 8.5		RCP4.5	
		Absolute	Deviation	Absolute	Deviation
2011-2040	Winter(Nov-Feb)	25.7	12.463	20.44	7.203
	Spring(Mar-Apr)	13.04	0.024	14.2	1.184
	Summer(May-June)	5.57	-0.027	8.48	2.883
	Monsoon(July-Aug)	50.34	14.601	52.43	16.691
	Autumn(Sep-Oct)	35.04	-0.352	63.36	27.968
	Annual (Average)	**129.69**	**26.7092**	**158.91**	**55.9292**
2041-2070	Winter(Nov-Feb)	13.57	0.333	15.16	1.923
	Spring(Mar-Apr)	12.16	-0.856	12.26	-0.756
	Summer(May-June)	6.07	0.473	6.95	1.353
	Monsoon(July-Aug)	44.75	9.011	44.64	8.901
	Autumn(Sep-Oct)	40.12	4.728	35.43	0.038
	Annual (Average)	**116.67**	**13.6892**	**114.44**	**11.4592**
2071-2100	Winter(Nov-Feb)	14.69	1.453	13.88	0.643
	Spring(Mar-Apr)	13.19	0.174	14.02	1.004
	Summer(May-June)	10.37	4.773	8.61	3.013
	Monsoon(July-Aug)	59.59	23.851	59.39	23.651
	Autumn(Sep-Oct)	57.69	22.298	52.7	17.308
	Annual (Average)	**155.53**	**52.5492**	**148.6**	**45.6192**

Baseline (1992-2013)	Rawal Dam (Mm³)
Winter (Nov-Feb)	13.237
Spring (Mar-Apr)	13.016
Summer (May-June)	5.597
Monsoon (July-Aug)	35.739
Autumn (Sep-Oct)	35.392
Annual	102.981

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The research concluded that

1. HEC-HMS used for simulation of rainfall-runoff characteristics of Rawal Dam proved to be efficient.
2. Future projections of climate change for Rawal dam station show increased precipitation throughout the century. The table below shows percentage of increase in precipitation under RCP8.5 and RCP4.5 for Rawal Dam for the three time slices used in the study.

Table 10: Percent Increase in Precipitation under Emission Scenarios at Rawal Dam Station

Time	RCP 8.5	RCP 4.5
2025s	12%	21%
2055s	10%	6%
2085s	18%	8%

3. The study concludes increase in potential stroage at Rawal dam due to increased precipitation both at Rawal Dam and Murree station. Table 12 shows the percentage increase in reservoir inflows due to increased precipitation in future.

Table 11: Percent Increase in Potential Storage at Rawal Dam under Emission Scenarios

Time	RCP 8.5	RCP 4.5
2025s	26%	54%
2055s	13%	11%
2085s	51%	44%

5.2 RECOMMENDATIONS

The present study envisages effect of change in precipitation on inflows of Rawal Dam. It can be refined/enhanced in future by

1. Incorporating more variables like effect of change of temperature and evapotranspiration on inflows of Rawal Dam.
2. By studying future demographic trends and their effect on the reservoir.
3. By studying adaptation strategies to changing environment for the reservoir.

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