Hydrological Response and Reservoir Operation Strategy under Climate Change - A Case Study of Simly Dam

By

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DEDICATED TO

MY FAMILY

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(Zubair Hafeez)

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LIST OF ABBREVIATIONS

CARIAA	Collaborative Adaptation Research Initiative in Africa and Asia
CDA	Capital Development Authority
CC	Climate Change
CMIP	Coupled Model Inter-comparison Project
CN	Curve Number
DEM	Digital Elevation Model
ERDAS	Earth Resources Data Analysis System
FAO USA	Food and Agriculture Organization United States of America
FDC	Flow Duration Curve
GCM	Global Circulation Model
GHG	Greenhouse Gas
GIS	Geographic Information System
HEC-HMS	Hydrologic Engineering Center Hydrological Modeling System
HEC-ResSIM	Hydrologic Engineering Center Reservoir System Simulation
Hi-AWARE	Himalayan Adaptation, Water and Resilience
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Pannell on Climate Change
MGD	Million Gallon per Day
MLC	Maximum Likelihood Classification
NIPS	National Institute of Population Studies
NS	Nash Sutcliff

PMD	Pakistan Meteorological Department
RCP	Representative Concentration Pathway
RMSE	Root Mean Square Error
RRV	Reliability, Resilience and Vulnerability
RS	Remote Sensing
SCS	Soil Conversion Service
SPD	Survey of Pakistan Datum
SRES	Special Report on Emissions Scenarios
SWAT	Soil and Water Assessment Tool
USGS	United Stated Geological Survey
WAPDA	Water and Power Development Authority
WUE	Water Use Efficiency

ABSTRACT

Climate change is reality now and fresh water resources are under threats in this context. The assessment of impacts of climatic variabilities on available water resources is necessary to identify adaptation strategies. Simly dam a key source of drinking water for Islamabad city is likely to be affected by such type of changes. In this study ERDAS IMAGINE and HEC-HMS were employed for land use classification and hydrological assessment of the catchment, respectively. Climate change projected precipitation data, derived under the medium and high emission scenarios namely RCP4.5 and RCP8.5, respectively, was extracted for Simly dam 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 wa used as input of HEC-HMS model to evaluate potential impacts of climate change on storage of water at Simly reservoir. 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). Frequency analysis was carried out to predict change in frequency of precipitation events. Initially three probability distributions Normal, Log-Normal and Gumbel distributions were considered, and finally best fit distribution was selected based on Chi-squared (X^2) and probability plotting test. HEC-HMS model was used to assess hydrological response of the catchment and sustainability of the reservoir to withstand against rainfall events of different return periods under present and future climate change conditions. Reservoir simulations were performed using HEC-ResSIM model, to address potential impacts of climate change on existing operational strategy of Simly reservoir. For this purpose, HEC-HMS generated inflows for above mentioned climate change scenarios were used as input of HEC-ResSIM model. Performance of the system was evaluated in terms of reliability, resilience, vulnerability and water use efficiency. Modification in current operational rule curves was applied and reservoir levels were simulated against projected inflows into Simly reservoir. It is anticipated that system performance would enhance under changing climate by adopting proposed changes in current operational rules curves.

Chapter 1

INTRODUCTION

1.1 BACKGROUND

Climate change is reality now and considered as great threat for fresh water resources. In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality (IPCC 2014). Hydrological changes may have impacts that are positive in some aspects, and negative in others (Kundzewicz et al. 2007). The beneficial impacts of the increases in runoff in some regions will be moderated by some negative effects, such as changes in the variability and seasonality (Minville et al. 2009).

Consequently, changes in the hydrological regimes will have effects on the storage and management of reservoirs (Christensen et al. 2004). Changing pattern and quantity of stream flows would affect the operational strategies of existing water resources system. Under the foreseen climatic variabilities, the water resource managers must develop the policies adapting to climate changes. IPCC supports the view that need for adaptation along with associated challenges is expected to increase with climate change (IPCC 2014).

Water resource managers have options to adapt structural and nonstructural measures to cope with consequences of climate change. The structural measures e.g. increasing sizes or number of dams, transferring water from catchment to other require large capital and resources. On other hand, non-structural measures e.g. modification of operational strategies incorporating water supply, hydropower and flood control, enable water resource managers to relieve negative impacts of climate change in simple ways.

Recently, much attention has been paid to the impacts of climate change on hydrological regime, however, fewer studies have investigated the impacts of climate change on the management of water resource systems (Minville, Brissette, Krau and Leconte 2009). Some studies conducted at different river basins by (Christensen, Wood, Voisin, Lettenmaier and Palmer 2004; VanRheenen et al. 2004;

Park and Kim 2014) considered the impacts of climate on management of water resources system but do not consider adaptive characteristics to minimize consequences of climate change. (Payne et al. 2004) conducted an adaptation study at water resources of the Columbia river basin. The results showed that adaptation could amplify the performance of the system. (Minville, Brissette, Krau and Leconte 2009) practiced a dynamic and stochastic optimization model to construct reservoir operational rule as adaptive measure to climate change for Peribonka River basin.

On other hand, among the global issues, growing population where hits many socio-economic parameters, is also increasing the thirst of water. It also has seen that population growth in metropolitan cities is greater than the nation as whole and Islamabad city (Capital of Pakistan) is considered as one of those cities. It is admitted fact that freshwater resources in such populated areas are likely to come under more pressure in the era of climate change and demand of adaptive strategy to climate change may happened as inevitable.

1.2 PROBLEM STATEMENT

Capital Development Authority (CDA) is responsible to provide drinking water for Islamabad city (Capital of Pakistan) from three main sources, reservoir built at Khanpur and Simly and few tube wells for pumping ground water. Fresh water resources in the capital are increasingly limited. The maximum cumulative water production from these three resources is 84 MGD in which Simly have its share with installed capacity of 42 million gallons/day. Whereas the average demand of water is 176 MGD and city have to face shortage of water almost throughout the year (CDA 2016). According to National Institute of Population Studies (NIPS), Islamabad, population of city may reach up to 13,22,809 in 2035 and 27,39,846 tills at the end of the century Figure 1.1.

It indicates that more water will be required in future and conditions could be worse than now. Meanwhile, there is also uncertainty about future state of climate and land use changes in the catchment. Simly dam a key source of drinking water for Islamabad city is highly vulnerable to such type of changes and require an integrated approach to manage its water resources system.

In the adverse effects of climate change, it is likely to increase frequency of occurrence of high intensity precipitation events. Although increasing or decreasing trend of extreme precipitation is not alike throughout the world but some specific regions are more vulnerable to it. Therefore, hydrological structures (e.g. dams, spillways) traditionally designed on the bases of statistics of historical records with assumption that frequency and intensity of precipitation based on past data is representative of occurrences in the future, call to review their sustainability and operational capacity under the threats of climate change.

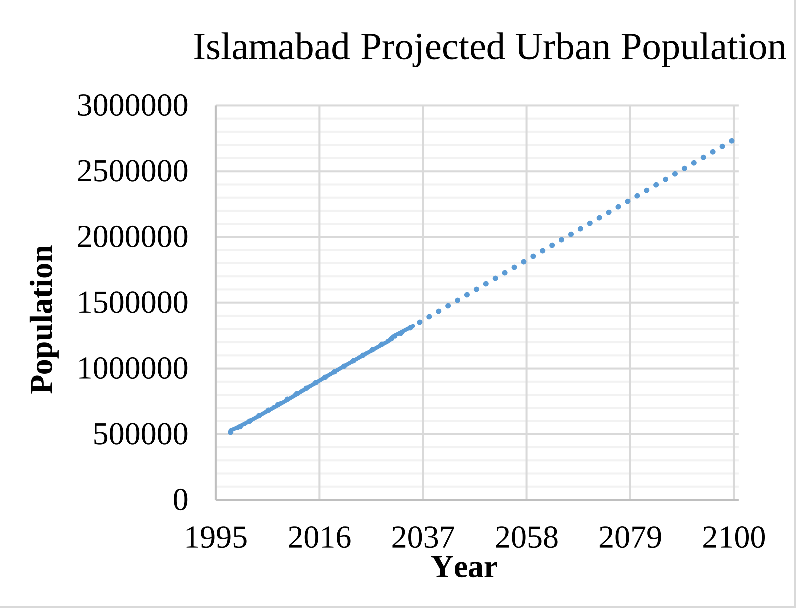


Figure 1.1 Projection of Population for Islamabad city by National Institute of Population Studies (NIPS)

In the light of above mentioned physical and demographic changes, there is increasing uncertainty for future state of water availability and its efficient use.

Previous studies for Simly catchment were mainly focused on qualitative measurements (Iram et al. 2009; Aziz et al. 2014; Hussain et al. 2014; Shahid et al. 2014) and yet, no study provides enough information to describe ongoing and upcoming challenges.

Therefore, it is necessary to quantify potential impacts of climate change on Simly reservoir and to identify best possible operational strategies.

1.3 OBJECTIVES OF STUDY

This study is planned to fulfill following major objectives.

1. Identification and assessment of land use changes in the catchment.
2. Application of rainfall runoff model to simulate hydrological response of Simly dam catchment.
3. Assessment of future water availability under climate change scenarios.
4. Application of frequency distribution to estimate change in frequency of precipitation events under climate change scenarios.
5. Optimization of different operational strategies for Simly reservoir under climate change.

1.4 SCOPE OF RESEARCH STUDY

This study exhibits land use changes in the Simly dam catchment, using an image processing software. A rainfall-runoff model is used to assess hydrological behavior of the catchment. A good calibrated and validated hydrological model is applied for evaluation of potential impacts of climate change on future water availability. Here, different frequency distributions are considered to find a best fir distribution for the study catchment. Frequency analyses are performed in respect to investigate change in frequency of high intensity precipitation events from current climate conditions to the end of the century. Optimization of reservoir operational rule curve is performed under different water supply and climate change scenarios.

1.5 ORGANIZATION OF THESIS

This thesis is organized in five chapters and detailed outline is described below.

Chapter 1 presents background of the study. In this chapter climate change and its few consequences on water resources system are described, shortly. Also, the problem statement, objectives of the study and scope of research work are described.

Chapter 2 is composed of literature review. In this chapter land use/cover changes and their impacts, hydrological models, Intergovernmental Panel on Climate Change (IPCC) emission scenarios of greenhouse gasses (GHG), impacts of climate change on hydrology, frequency analysis and reservoir operational rules are discussed.

Chapter 3 describe location map of study area and salient features of the Simly reservoir and hydro-meteorological stations in the catchment. Preliminary analyses are performed to describe hydro-meteorological conditions of the catchment. In this chapter data sources, selection of models and software's and methodology of research work is explained.

Chapter 4 is composed of results and discussion. In this chapter outcomes of research work are presented. Statistical analyses to describe model's performance and potential impacts of climate change on future water availability are discussed. Here, change in frequency of precipitation events under climate change scenarios is addressed. This chapter also presents current operational capacity of Simly reservoir and proposed operational strategies under climate change.

Chapter 5 is organized to explain conclusions drawn from this research work and corresponding recommendations.

Chapter 2

LITERATURE REVIEW

2.1 IMAGE PROCESSING TERMINOLOGIES AND TOOLS

2.1.1 Land Cover

It relates to the type of features present on the surface of the earth e.g. wheat fields, lake, river, buildings and roads.

2.1.2 Land Use

It relates to the human activity or economic functions associated with a specific piece of land, residential area or industry.

In simple words, the difference between these two terms can be describes as that land cover designates the physical cover over the earth such as forest or bare land, whereas land use refers to use of land by human activities.

2.1.3 Land Use/Cover Classification Tools

For land use change detection, data selection is very important. The formal ways to collect data information like topographic maps, soil maps, field survey and sampling are costly, time consuming, less efficient and small area cover methods. Another reliable source is remote sensing. It is quick, efficient, reliable, less costly, frequently available and suitable especially for those areas where field visit is not possible. Land use changes can be detected by comparing multiyear satellite imagery through image processing. (Rémi et al. 2007; Chaudhary et al. 2008) have used satellite images and applied an image processing software ERDAS-IMAGINE for land use change detection. They have used supervised classification method and found that with maximum number of classes, accuracy can be obtained by assigning Maximum Likelihood Classification (MLC) rule. Supervised classification is a process to assign a specific class to the sample pixels of same characteristics and image processing software apply it on other unknown pixels with in the image. On other hand in unsupervised classification, identification and categorization of natural groupings of spectral values in the multispectral image is done by software without any input of the analyst. (Shahid, Gabriel, Nabi, Haider, Khan and Shah 2014) have applied unsupervised classification for land use change detection over Simly dam catchment for three distinct years 1992, 2000 & 2010. (Donald I. M.Enderle 2005) suggest to use both methods of classification if greater accuracy is required for land use change detection.

2.1.4 Impacts of Land Use Changes

Land use changes play a larger role to influence runoff volume and peak discharges. When undeveloped areas like forests and grasslands are converted into developed areas (roofs, roads, sidewalks, parking lots and buildings), its permeable surface is replaced by impermeable surface and infiltration capacity of the catchment decreases, which leads to change in hydrological response of the catchment (high flood peaks with reduced lag time), causing increase into ditches and streams runoff. (Schultz 1995) work support this argument, he analyzed hydrological impacts of tow possible land use change scenarios (urbanization and dead forest) in the catchment of river Nims in Germany and found that both scenarios deteriorate flood conditions. And urbanization which results in greatly reduced soil water storage capacity than deforestation, yields more flood peaks (about 50% higher) and significant increase in runoff with steeper rising and recession limb of hydrograph. (Loi 2010) researched the effects of land use change on runoff as well as sedimentation making use of SWAT in Dong Nai watershed-Vietnam and found significant increase in runoff and sedimentation when deforestation triggered in the catchment. (Suriya and Mudgal 2012) classified land use changes in Thirusoolam watershed (299.75 Km^2) in India, from year 1975 to 2005 and investigated the hydrological response to these changes. As far as built up area increased from 70.30 Km^2 to 107.64 Km^2 (53% increase) in thirty years, flood plain area increased from 31.70 Km^2 to 36.61 Km^2 for 100 year return period rainfall, in same way flood depth increased from 3.71m in 1976 to 4.55 m in 2005. (Ali et al. 2011) applied a rainfall-runoff model to check impacts of future master plan on hydrological behavior of upper part of Lai Nullah Basin lies in Islamabad (Capital of Pakistan). In present land use distribution pattern, urbanized area which accounts for 45.5% of total watershed area, in future would increase up to 64.25% of the total watershed area. It has been observed that for five different rainfall events of different magnitude from 35 mm to 88 mm, runoff volume and peak discharge increases in a range of 58% to 100% and 45.4% to 83.3% respectively, from present to future land use conditions.

2.2 HYDROLOGICAL MODELLING APPROACHES

Hydrological models, however, are developed to understand the hydrological cycle and physical law of water movement. They intend to statistically explain the response of different components of hydrological system for climate variables and are useful tool to conduct impact studies. On the bases of process depiction in the catchment, hydrological models can be categorized in three main classes Lumped, distributed and semi distributed models.

2.2.1 Lumped models

Lumped hydrological models usually do not offer to change hydrological parameters inside the watershed and therefore, watershed response can be assessed only at the outlet, without gathering information about individual response of sub-basins.

2.2.2 Distributed Model

Fully distributed models are discretized into more detailed grids and capable of capturing the spatial distribution of input variables including metrological conditions (rainfall, temperature etc.) and physical parameters (land use, soil, elevation etc.) for each defined grid. They perform grid-point calculations. So, distributed models are data intensive. They need quality data, hard to configure and they require greater simulation and calibration time.

2.2.3 Semi-distributed Model

Parameters regarding semi-distributed (simplified distributed) models are permitted to differ spatially by means of splitting the catchment into a number of small sub-basins units. Each sub-basin has its own uniform characteristics and unique discharge point. The main advantage of semi-distributed models is that their composition is physically-based compared to the composition of lumped models, and perhaps they are less challenging in terms of data requirements when compared with completely distributed models. SWAT, HEC-HMS and HBV are deliberated as semi-distributed models. In this respect, (Cunderlik 2003) made comparison among nine different semi-distributed hydrological models and found HEC-HMS one of the best semi distributed hydrological model. HEC-HMS is user friendly software to model hydrological characteristics of a catchment.

2.3 IMPACTS OF CLIMATE CHANGE

Climate change is referred to as a change in statistical distribution of weather pattern at global or regional scale and change lasts for extended period. Numerous factors are blamed for climate change happening e.g. global warming, variations in solar radiation received by Earth, plate tectonics, volcanic eruptions and biotic processes.

At observation end climate change is reality now and evident from increasing average global air and ocean temperature, widespread snow melting and rising sea level. Climate scientists are continuously making efforts to anticipate future climate change.

2.3.1 Climate Change Scenarios

Intergovernmental Panel on Climate Change (IPCC) release greenhouse gas (GHG) emission scenarios to derive Global Circulation Models (GCMs). Scenarios are alternative picture of how future might be reveal and are an appropriate tool to analyze influence of driving forces (such as technological change, demographic and socio-economic development) on emission outcomes and to assess the associated uncertainties. In 1992, IPCC released emission scenario IS92 and following Special Report on Emissions Scenarios (SRES) in 2000 and latest scenarios released in 2014 are named as representative concentration pathways (RCP).

2.3.1.1 Representative Concentration Pathways

The name “representative concentration pathways” was chosen to emphasize the rationale behind their use. RCPs are referred to as pathways in respect to emphasize that their primary purpose is to provide time-dependent projections of atmospheric greenhouse gas (GHG) concentrations. In addition, the term pathway is meant to emphasize that it is not only a specific long-term the trajectory that is taken over time to reach that outcome. They are representative in that they are one of several different scenarios that have similar radiative forcing and emissions characteristics (Moss et al. 2008).

The four pathways RCP2.6, RCP4.5, RCP6 and RCP8.5 are named after their radiative forcing values 2.6 Wm^{-2}, 4.5 Wm^{-2}, 6Wm^{-2} and 8.5Wm^{-2} respectively, in the year 2100 relative to pre-industrial period.

2.3.2 Hydrological impacts of Climate Change

Hydrological models enable one to understand potential impacts of climatic variability on hydrology of the catchment. In this regard, GCMs are best tools to extract climate change information, but their outputs cannot be used directly for impacts studies, because of their coarser resolution. However, downscaling techniques make it possible to fulfill small scale requirements by impact community.

Downscaled climate data can be used as input of hydrological model to simulate future discharges in order to estimate future water availability. Much attention has been paid for estimate of future runoff in response to climate change using different hydrological models e.g. (Dibike and Coulibaly 2005; Christensen and Lettenmaier 2006; Yimer et al. 2009; Eum and Simonovic 2010; Zareian et al. 2014). (Yimer, Jonoski and Van Griensven 2009) used SDSM model to downscale the GCM and incorporated the output into HEC-HMS model (calibrated and validated against observed data) to assess the impacts of climate change on stream flow in the Beles River. (Meenu et al. 2013) have incorporated HEC-HMS with downscaled data, to estimate hydrological impacts of climate change on Tunga-Bhadra river catchment.

2.4 FREQUENCY ANALYSIS

Hydrological systems are considered vulnerable to extreme precipitation events causing floods. These events are inversely linked to their frequency of occurrence. Severe hydrological events rarely occur but their extent is potentially very high. In some cases, challenging for hydrological structures. Hydrologists consider this factor at time of design and conduct frequency analysis to estimate intensity of extreme precipitation events. Frequency analysis use hydrological data to relate magnitude of severe events with their frequency of occurrence. This data is treated as space and time independent. Frequency analysis assume that climatology of data sample will not change in future. On other hand climate change may energize the current state of hydrological system and would affect frequency of precipitation events occurrence.

It is evident from literature review that in last few decades increasing trend of high intensity precipitation events is very common and assessed by (Hundecha and Bárdossy 2005) in Germany, (Zhai et al. 2005) in China, (Arnbjerg-Nielsen 2006) in Denmark, (New et al. 2006) African countries,(Goswami et al. 2006) in India, (Shahid 2011) in Bangladesh, and (Zahid and Rasul 2011) in Pakistan.

It is investigated by (Alexander et al. 2006; Donat et al. 2013; Fischer et al. 2014) that at global and continental scale world is susceptible to higher intensity precipitation events. (Christensen et al. 2007) in their work predict that climate change can significantly effects frequency and intensity of precipitation events in many regions and very likely in South Asia. (IPCC 2013) states that warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia.

In respect to the global warming, (O'Gorman and Schneider 2009; Boucher et al. 2013), say that heavy rainfalls will occur more frequently in a warmer world.

Researchers are making continuous efforts to quantify potential climate change impacts on frequency of severe events from larger scale to more specific areas. In this manner, (Camici et al. 2013) have applied different statistical downscaling techniques to two different GCMs (Global Circulation Models) and addressed the impacts of climate change on flood frequency. (Kay et al. 2009) explains that although GSM’s structure is great source of uncertainty involved in frequency analysis, so it is recommended to use several GCM’s scenarios for assessment of change in frequency of climatic extremes (Veijalainen et al. 2010).

In order to assess find hydrological response of the catchment against extreme precipitation events, (Fischer, Sedláček, Hawkins and Knutti 2014) have used HEC-HMS to check the response of projected changes in 6-hour duration, 100-year design-storm depth, calculated by regional frequency analysis under several climate scenarios for a watershed in Las Vegas Valley, Nevada.

2.5 RESERVOIR OPERATIONAL RULE CURVES

Reservoir operational rules provide a guidance for reservoir operators to make water release decisions. Simply, operator is to release water as necessary to achieve desired storage level for the time of year. These rules could be consisting of a curve or family of curves, generally depend on detailed sequential analysis of critical hydrologic conditions and demands.

A major change in inflow pattern or volume may largely affect functionality of operational rules.

2.5.1 Methods and Techniques to Develop Rule Curve

The rule curves are derived in accordance with the type and purpose of reservoir. The derivation also depends on operational strategy from single to multi-reservoir system. From literature view, it is found that following methods and techniques are most commonly used by researchers to derive operational rules.

- Trial and error method (Titus and Putuhena 2016)
- Decision tree algorithm (Wei and Hsu 2009)
- Linear programming (LP) (Loucks and Dorfman 1975)
- Non-linear programming (NLP) (Yeh 1985)
- Dynamic programming (DP) (Loucks et al. 2005)
- Genetic algorithm (GA) (Chang et al. 2005)
- DP with principle progressive optimality (DP-PPO) (Chaleeraktrakoon and Kangrang 2007)
- Parameter-Simulation-Optimization (PSO) (Celeste and Billib 2009)

2.6 ADAPTIVE RESERVOIR OPERATIONAL STRATEGIES TO CLIMATE CHANGE

Climate change adaptation is a way to limit the impacts of climate change at some extent. Its undertaking of consistent actions to reduce the vulnerability of climate change. Also, there are limitations to its effectiveness for greater magnitude and rate of climate change.

Identification of possible adaptation strategies and addressing extent of climate change, is key to reduce risk of disasters. Adaptation options exist in all sectors, but their context for implementation and potential to reduce climate-related risks varies across sectors and regions (IPCC 2014).

(Vonk et al. 2014) addressed the operational strategies of a Xinanjiang-Fuchun-jiang reservoir under climate change scenarios, and found that it’s very effective strategy to reduce the impact of climate change but could not completely restore the system in case of Xinanjiang-Fuchun-jiang reservoir.

Chapter 3

METHODOLOGY

3.1 STUDY AREA

The present study conducted on Simly dam catchment located North-East of Islamabad (i.e. Capital of Pakistan) with an area of 160 km^2, drains into Soan River which originated from Murree Hills (Figure 3.1).

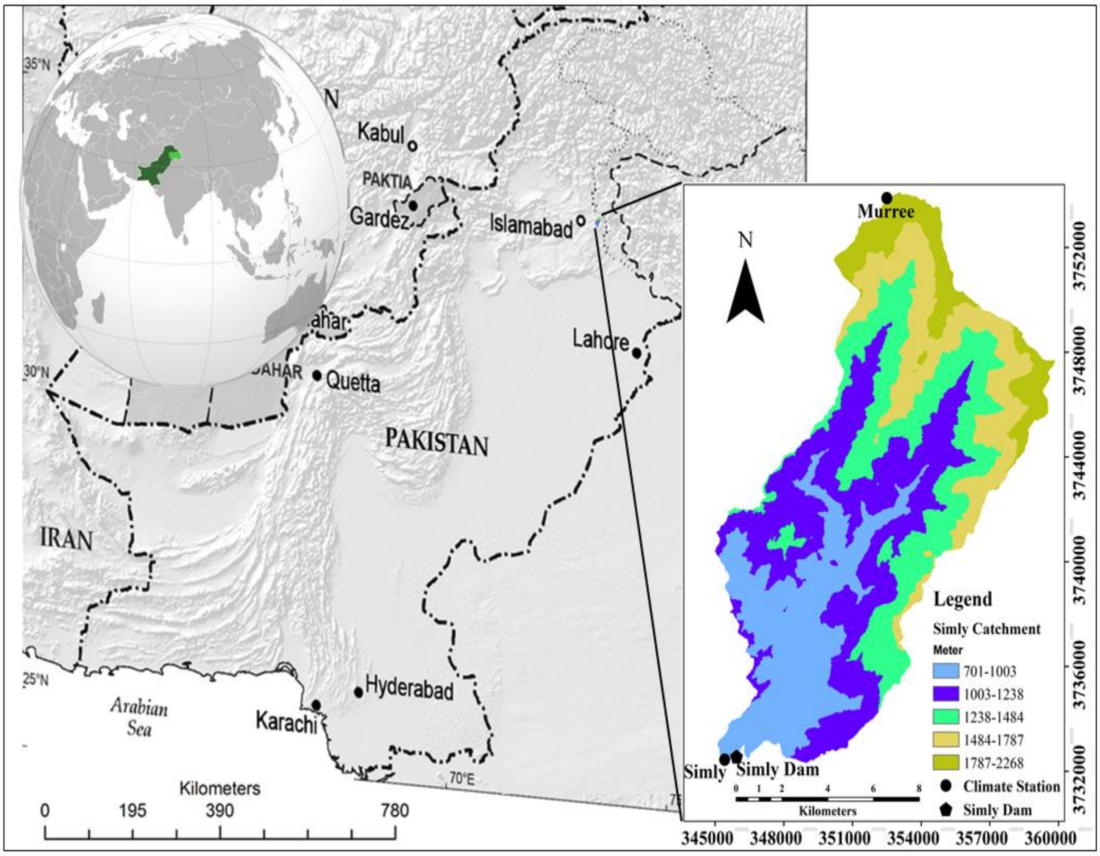


Figure 3.1 Location Map of Simly Reservoir

Almost 23 km long and 7 km wide, Simly dam catchment covers an elevation range from 678 m a.s.l. to 2275 m a.s.l. with mean elevation of 1270 m a.s.l. More than 60% of catchment is covered by forest and bushes (Hussain, Khaliq, Irfan and Khan 2014). There are two climate stations in the catchment i.e. Murree and Simly, with mean annual precipitation of 1725 and 1176 mm, respectively based on 31 years record (1983-2013). Mainly the catchment receives precipitation in the form of rainfall through a year with scanty snowfall occurring around mid of winter season only at higher altitude, moreover basin-wide maximum rainfall happens in monsoon period (469 mm) i.e. almost 36% of total annual precipitation (Figure 1). Based on 1998-2013 period, the average annual storage available at Simly dam is 65 Million cubic meter (Mm^3), with main contribution during monsoon (Jul-Aug) period (26.8 Mm^3). However, during winter (Nov-Feb), autumn (Sep-Oct) and spring (Mar-Apr) storage is available which ranges from 10 to 13 Mm^3, while minimum storage of 3.2 Mm^3 is available during summer season.

Table 3.1 Salient Features of Simly Dam Catchment

Climate Station	**Latitude**	**Longitude**	**Elevation (m.a.s.l)**	**Data Time Range**		**Mean Annual Precipitation (mm)**	**Source**
Murree	33° 55' N	73° 23' E	2167 m	Daily	1983-2013	1720	PMD
				Monthly	1983-2013		
Simly	33° 43' N	73° 20' E	700 m	Daily	2004-2013	1176	CDA
				Monthly	1983-2013		

Seasonal Distribution of Precipitation (1983-2013)					
	Winter (Nov-Feb)	Spring (Marc-Apr)	Summer (May-Jun)	Monsoon (Jul-Aug)	Autumn (Sep-Oct)
Murree	92	148	112	312	104
Simly	49	83	62	274	71

Simly reservoir with gross storage of 46.68 Mm^3 (at 705.8 m a.s.l.) was commissioned in 1983 with primary purpose to provide drinking water supply to the residents of Islamabad city by Capital Development Authority (CDA)and the installed capacity of the filtration plant at Simly dam is 2.21 m^3/s (42 Million gallon per day). The average annual outflow through filtration plant is 48 Mm^{3,} based on record 1998-2013. According to hydrographic survey carried out by CDA in 2013, the reservoir current gross storage is 36.88 Mm^3, reduced by 21% since it commissioned and at maximum water level (MWL, 706.4 m a.s.l.), the reservoir can store 37.8 Mm^3 of water covering water surface area of almost 2 km^2.

3.2 DATA SETS

3.2.1 Topographic Data

The Advanced Space borne Thermal Emission and Reflection Global Digital Elevation Model (ASTER GDEM) of 30×30 m resolution was used to extract terrain information of the Simly Dam catchment and delineation of the catchment area. The catchment area is divided into three sub-basins and several key features were extracted like: elevation, area, etc are given in Table 3.1. Further on the bases of hydrographic survey, reservoir elevation-storage relationships for 1983, 2004 and 2013 were acquired from Capital Development Authority (CDA) to extract the information of reservoir levels during reservoir simulation

3.2.2 Hydro-Climatic Data

Historic hydro-climatis data of Simly dam catchment is managed by Pakistan Meteorological Department (PMD) and (CDA. The daily and monthly precipitation data of Murree station (1983-2013) was acquired from PMD, while for Simly station precipitation at monthly (1983-2013) and daily (2004-2013) time scale was obtained from CDA. Other essential dataset was made available by CDA includes: reservoir elevation storage relationships for 3 years (1983, 2004, 2013), daily (2004-2013) and monthly inflows (1998-2013) into reservoir, daily pan evaporation (2004-2013), daily reservoir water levels (2004-2013), daily (2004-2013) and monthly outflows (1998-2013) from spillway and filtration plant for water supply, spillway rating curve and reservoir operational rule curves. The observed monthly hydro-climatic dataset for a base period of 28 years (1998-2010) was used as reference which is hereafter referred to as baseline (observed).

For projected changes in storage of Simly reservoir under changing climate, the projected daily precipitation was extracted from Himalayan Adaptation Water and Resilience (HI-AWARE) product for Indus, Ganges and Brahmaputra (IGB) River basins developed under Representative Concentration Pathways i.e. RCP4.5 and RCP8.5 scenarios. The methodology of selection of eight (8) Global Circulation Models (GCMs) from 169 GCMs in Coupled Model Inter-comparison Project 5 (CMIP5) repository is described in detail by (Lutz et al. 2016). The selected 8 GCMs runs are comprised of bcc-csm1-1_rcp85_r1i1p1, CanESM2_rcp85_r3i1p1, CMCC-

CMS_rcp85_r1i1p1, inmcm4_rcp85_r1i1p1, BNU-ESM_rcp45_r1i1p1, CMCC-CMS_rcp45_r1i1p1, inmcm4_rcp45_r1i1p1, and CSIRO-Mk3-6-0_rcp45_r4i1p1. Under HI-AWARE project, the selected GCMs are downscaled at daily temporal and 10×10 km grid size spatial resolution on the basis of RCP4.5 and RCP8.5, using empirical-statistical downscaling technique, mentioned by (Lutz, ter Maat, Biemans, Shrestha, Wester and Immerzeel 2016), which was acquired to study the projected changes in the precipitation and hydrological regime of the Simly dam catchment. The reference climatic dataset for HI-AWARE product spans from 1981-2010, while for future projections available till end of 21st century.

3.2.3 Land Cover and Soil Dataset

The satellite image of Landsat 7 for the year 2004 and 2013, freely available U.S. Geological Survey website (https://earthexplorer.usgs.gov/) at 30×30 m resolution was used to extract land cover information of Simly dam catchment, however the information of soil datawas extracted from freely available Food and Agriculture Organization (FAO) harmonized soil map of the world (http://www.fao.org/home/en/) at 1:5,000,000 scale, which is undoubtedly most comprehensive soil map (Sombroek, 1989; Nachtergaele, 1996). By combining the soil data and land cover, hydrological parameters like hydrological soil groups (HSGs) and curve number (CN) were estimated for the hydrological model.

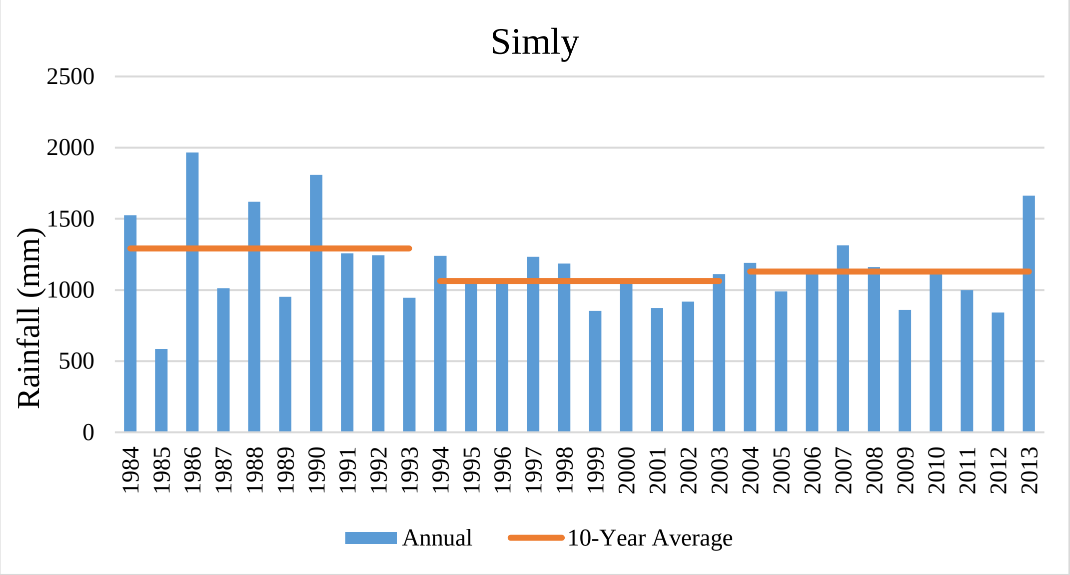
3.3 PRELIMINARY DATA ANALYSIS

Preliminary analyses were performed to address climatic behavior of Simly dam catchment.

3.3.1 Precipitation Analysis

The analysis on change in precipitation recorded at Murre and Simly climate station at annually bases are presented in *Figure 3.2*. Murre station is located at higher elevation (2167 m a.s.l) than Simly climate station (700 m a.s.l). Total annual precipitation at Murre station is greater than Simly station.

Analysis show that there is decreasing trend of precipitation at both station. At Murre station 10-year average precipitation has been reduced from 1885 mm to 1546 mm for period (1984-93) to (2004-13). Similarly, at Simly climate station average precipitation 1292 mm for period (1984-93) has been reduced to 1130 mm for period (2004-13).



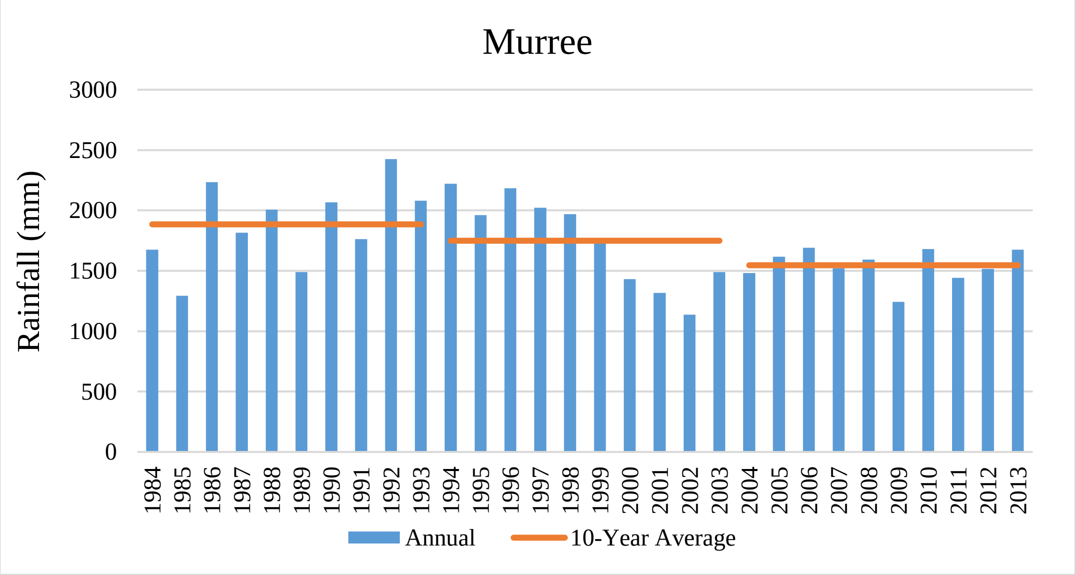


Figure 3.2 Annual and 10-year average Precipitation

3.3.2 Flow Duration Curve

Flow duration curve analysis was performed at Simly reservoir daily inflow data available from 2004-13. *Figure 3.3* shows hydrological behavior of the Simly dam catchment. Analysis show that a discharge greater than 2.05 m^3/s is averagely available for almost 77 days of the year. This amount of water (2.05 m^3/s) is considered as safe yield for water supply in operational rules of Simly reservoir.

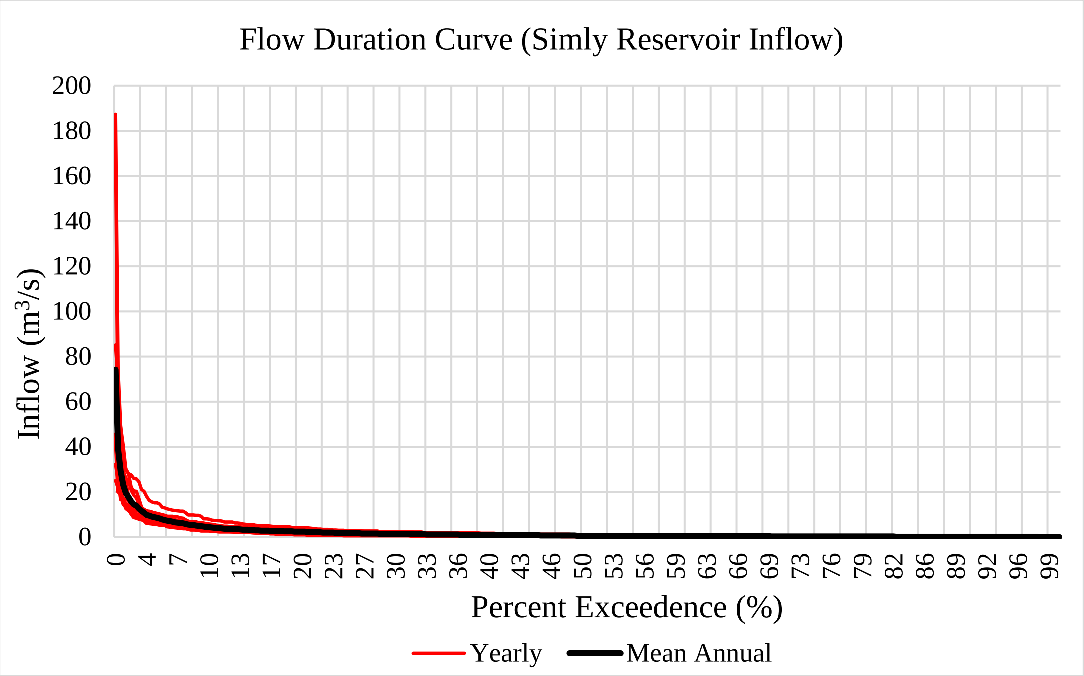


Figure 3.3 Flow Duration Curve (FDC) for Simly Reservoir Daily Inflow (2004-2013).

Figure 3.4 shows the flow duration curve for different years from period 2004-2013 and the water supply equivalent to amount of 2.05 m^3/s was not provided more that 25 % days of the year.

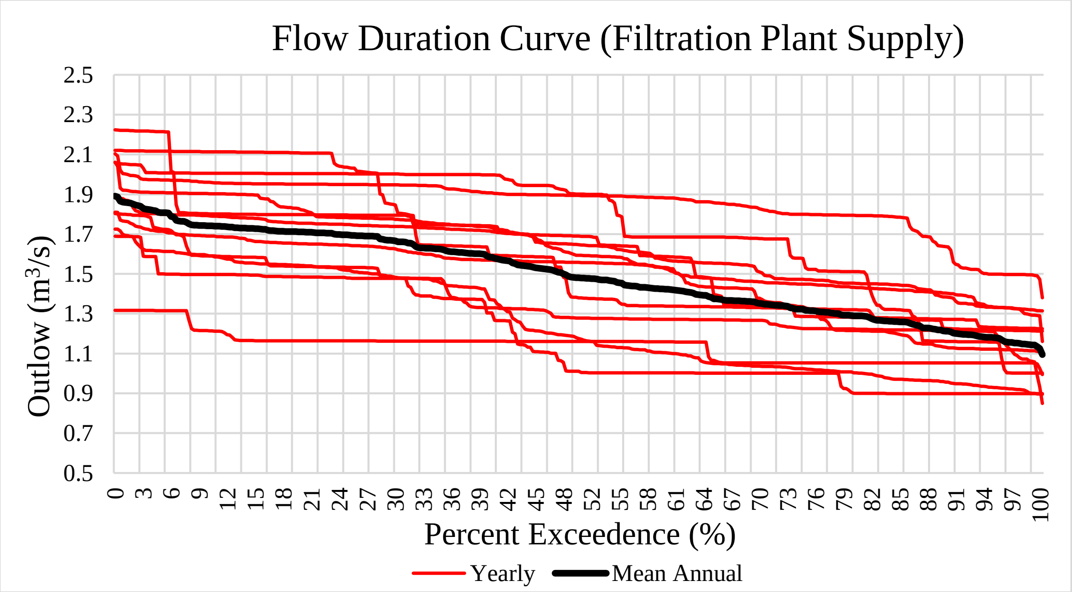


Figure 3.4 Flow Duration Curve (FDC) for Simly Reservoir releases through filtration plant

Also, some years did not provide this amount of water even a single day. For a period 2004-2013, the number of days with supply of 2.05 m3/s are not, averagely, more than 12 days/year.

On the bases of monthly inflow record (1998-2013) at Simly reservoir average inflow is 68 Mm^3. Due to uneven temporal distribution of inflow, averagely, 36.68Mm^3 comes into monsoon months (Jul-Sep). It seems that supply of 2.05 m^3/s per day throughout the year could be challenging in any way.

3.4 METHODOLOGICAL FRAMEWORK

The Landsat images were processed in ERDAS Imagine, to determine percentage and presence of different land cover classes in the catchment. Further the output was used to create CN grid (input of HEC-HMS). The daily runoffs generated from the catchment and Simly dam reservoir levels were simulated by using HEC-HMS i.e. rainfall-runoff model. HEC-HMS model was calibrated and validated for periods of 4 years (2004-2007) and 3 years (2011-2013), respectively. The accuracy of the model calibration and validation was assessed by using three well-known statistical descriptors, which are Nash-Sutcliffe coefficient (NS), root mean square error (RMSE) and coefficient of determination (R^2), to study the relationship between simulated and observed daily incoming runoffs and reservoir levels at Simly dam. Frequency analysis were performed to evaluate best fitted frequency distribution and to estimate probability of reoccurrence of same magnitude precipitation events. The response of catchment against rainfall events of different return period was assessed and monitored its impacts on reservoir in terms of reservoir level and safety against overtopping. While using best fitted frequency distribution, the projected impacts of climate change on frequency of precipitation events was estimated. The projected climate date under RCP8.5 and RCP4.5 was extracted from IGB dataset and after bias correction used it into HEC-HMS to simulate future inflows into Simly reservoir under different climate change scenarios. The inflows generated from HEC-HMS were used as input of HEC-ResSIM to simulate reservoir level. With the help of HEC-ResSIM, the performance of reservoir operational strategy was evaluated. The methodology used in this study is described schematically in Figure 3.5.

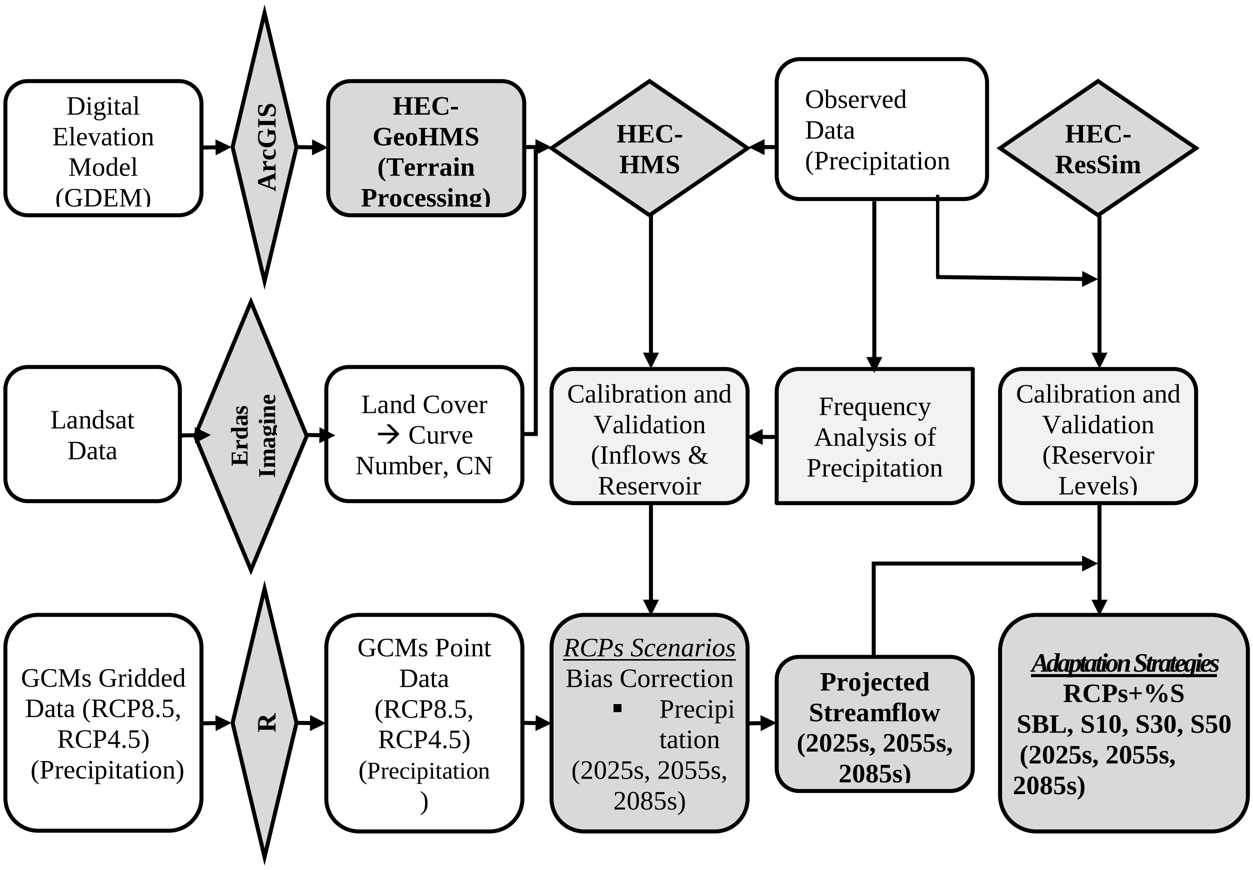


Figure 3.5 Schematic Diagram of Methodology

3.4.1 Land Use Classification

Land use classification to detect changes occurred in the catchment from year 2004 to 2013 was performed through image processing tool available in ERDAS Imagine 9.3. Six main classes were initially recognized in the catchment as water body, bare land, agriculture, forest, bushes and built up land. The Landsat images of two different years (2004 & 2013) and same month (July) were extracted for Simly catchment and entertained with supervised classification. It's simple, easy and widely used technique. Final classified layer was used as input of HEC-GeoHMS to generate curve number grid.

3.4.2 Application of Hydrological Model (HEC-HMS)

HEC-HMS is a hydrological model developed by Hydrologic Engineering Center of U.S Army Corps of Engineers (USACE 2000) to simulate rainfall-runoff process which enables its user to select a range of different methods to simulate different hydrological processes based on data availability and objectives of the study. The applications of HEC-HMS model have been practiced in many studies as an efficient hydrological model to simulate rainfall runoff processes (Anderson et al. 2000; Yusop et al. 2007; Yimer, Jonoski and Van Griensven 2009; Verma et al. 2010). HEC-HMS consists of four components i.e. basin, meteorological, control specification, and time series). The detail explanation of model structure can be found in user's (USACE 2015) and technical reference manual (USACE 2000). HEC-HMS basin component offers various methods (Azmat et al. 2015) to model surface storage, loss, transfer, channel routing and baseflow, however, Surface Method (surface storage), Deficit and Constant (loss), SCS Unit Hydrograph (transform), Muskingum (channel routing) and Constant Monthly (baseflow) methods were used in current study. The Geospatial Hydrologic Modeling System Extension (HEC-GeoHMS) was used to delineate and obtain the physical characteristics (like: slope, length, area, etc) of Simly catchment from ASTER GDEM. The Simly catchment is further sub-divided into three (3) sub-basins for application of HEC-HMS. ERDAS Imagine is an image processing tool, utilized to extract the land cover classification using supervised classification technique (Duda et al. 2002), on Landsat 7 image. The Simly catchment was classified into six land cover categories including forest, bare land, built-up area, bushes, agriculture and water. Based on the soil properties of the catchment extracted from FAO world soil map, soil was classified into hydrological soil groups (HSGs) C using the criteria defined by (Chow et al. 1988; Debo et al. 2002). Lumped curve number, land cover and HSGs were merged to generate composite curve number grid. Simly catchment was considered with an average Antecedent Moisture Condition i.e. AMC(II), of the pervious surfaces prior to rainfall event used for modelling purpose.

The parameters of HEC-HMS to set are initial storage I_s, maximum storage M_s, initial deficit I_d, maximum deficit M_d, constant rate C_r, impervious I_m, curve number CN, lag time t_{lag}, constant monthly discharge Q_c, Muskingum travel time K and Muskingum dimensionless weight X. In Surface method, maximum storage is important parameter used to estimate the surface storage, which was estimated from literature review. The Deficit and Constant method used to estimate the rainfall loss, where constant rate and imperviousness are most important parameters, which were extracted by using information of land cover classes. Curve number CN were calculated by using land cover, hydrological conditions and hydrological soil groups (HSGs), while for SCE Unit Hydrograph method, the lag times for transformation of rainfall into runoff were estimated directly using SCS lag equation i.e. an empirical approach developed by the SCS (1972). For a particular month during the simulation period, a constant monthly discharge as baseflow was extracted from observed average monthly runoff values during non-rainy days in the same month. Muskingum *K* and *X* were estimated by trial and error.

3.4.2.1 Model Performance Evaluation

Performance of the hydrological model is explained in terms of coefficient of determination (R^2), Nash Sutcliff coefficient (Ns) and root mean square error (RMSE).

3.4.2.1.1 Coefficient of Determination (R^2)

The coefficient of determination, denoted as (R^2), is used to indicate proportion of the variance in the dependent variable (x), that is predictable from the independent variable (y).

It is square of the correlation (r) between predicted and actual values. and ranges from 0 to 1. With linear regression, the coefficient of determination is also equal to the square of the correlation. An R^2 of 0 means that the dependent variable cannot be predicted from the independent variable. An R^2 of 1 means the dependent variable can be predicted without error from the independent variable. An R^2 between 0 and 1 indicates the extent to which the dependent variable is predictable.

Mathematically, coefficient of determination (R^2) is presented as:

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

where N is the number of observations used to fit the model, Σ is the summation symbol, x_i is the x value for observation i, $\bar{x}$ is the mean x value, y_i is the y value for observation i, $\bar{y}$ is the mean y value, σ_x is the standard deviation of x, and σ_y is the standard deviation of y.

3.4.2.1.2 Nash Sutcliff Coefficient (Ns)

The Nash–Sutcliffe model efficiency coefficient is used to assess the predictive power of hydrological models. The value ranges from $-\infty$ to 1. It is defined as

$$Ns = 1 - \frac{\Sigma(\mathrm{Qo} - \mathrm{Qm})^2}{\Sigma(\mathrm{Qo} - \overline{\mathrm{Qo}})^2}$$

Here, Q_o is observed flow, Q_m is modeled flow and $\overline{Q_o}$ is mean of Observed flow.

3.4.2.1.3 Root Mean Square Error (RMSE)

The Root Mean Square Error (**RMSE**) (also called the root mean square deviation, RMSD) is a frequently used measure of the difference between values predicted by a model and the values observed at station. These individual differences are also called residuals, and the RMSE serves to aggregate them into a single measure of predictive power.

The RMSE of a model prediction with respect to the estimated variable X_{model} is defined as the square root of the mean squared error:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model,i})^2}{n}}$$

where X_{obs} is observed values and X_{model} is modelled values at time/place i.

3.4.3 Frequency Analysis

Frequency distributions allow to estimate intensity of precipitation for a specific return period. To our knowledge, no specific distribution is assigned or proposed for this region or catchment. However, from a wide range of probability distributions, here, most commonly used distributions Normal, Log-Normal and Gumball distribution were initially considered. A data series consist of annual maximum precipitation for 24-hr duration, covering 12 years (2002-2013) for Simly station and 31 years (1983-2013) for Murree station was used to perform frequency analysis using frequency factor as mentioned in Equation 1.

$$Xt = \overline{X} + K(\sigma) \qquad \text{Equation 1}$$

Here, "Xt" is 24 hr. maximum precipitation amount for given return period, "$\overline{X}$" is mean, “K” is frequency factor and “σ” is standard deviation. This is simplest method and applicable for all mentioned distributions, only differ by its definition of frequency factor which varies from one distribution to other. Frequency factor is most sensitive parameter, largely influence the estimation of magnitude of extreme event. Detailed methodology is described in (Chow et al. 1988). Here, K =z for Normal and Log-Normal Distribution and K= Kt for Extreme Value- 1 (Gumbel) distribution.

For Normal and Log-Normal

$$z = w - \frac{2.515517 + 0.802853w + 0.010328w^2}{1 + 1.432788w + 0.189269w^2 + 0.001308w^3} \qquad \text{Equation 2}$$

and $$w = \sqrt{ln(\frac{1}{P})} \qquad \text{Equation 3}$$

For Gumbel,

$$Kt = -\frac{\sqrt{6}}{\pi}[0.5772 + ln(ln(\frac{T}{T-1}))] \qquad \text{Equation 4}$$

When $$T = \frac{1}{P} \qquad \text{Equation 5}$$

The plotting position was defined by Weibull formula as

$$P = \frac{m}{n+1} \qquad \text{Equation 6}$$

Where “m” is the rank and “n” represents number of years. For annual maximum series U.S Water Resources Council use this formula as standard plotting position (Chow, Maidment and Mays 1988; VanRheenen, Wood, Palmer and Lettenmaier 2004)

To find best fit distribution, two different tests Chi-Square test (x^2) and probability plot were used. Chi-Squared test (x^2) procedure is briefly explained in (Chow, Maidment and Mays 1988). For probability plot test, linearity is described using (R^2) and for this purpose observed data must plot against reduced variate of corresponding distribution. However, (X) data series is needed to plot against reduced variate z as explained in Equation 2 for Normal distribution and Log (x) in case of Log-Normal distribution. For Gumbel distribution reduced variate y is found using Equation 7 (Marriott and Hames 2007). This approach is equivalent to use probability plot paper (Chow, Maidment and Mays 1988). Comparing to other tests, probability plotting is advantageous to use because of its graphical and numerical representation.

$$y = -ln[ln(1 - \frac{1}{T})] \qquad \text{Equation 7}$$

For frequency analyses, a best fit distribution was used for estimation of 24-hr maximum rainfall depth for given return period. At later stage, hydrological response of the catchment and consequently reservoir capacity to store water and spill surplus water to avoid from overtopping against different return period, was analyzed.

3.4.4 Application of Reservoir Simulation Model (HEC-ResSIM)

HEC-ResSIM model is a reservoir system simulation developed by Hydrologic Engineering Center of USACE ((USACE 2013) to optimize reservoir operations for various operational goals/constraints. HEC-ResSIM is unique among reservoir simulation models because it attempts to reproduce the decision-making processes that reservoir operators traditionally used to plan/schedule water releases (Park and Kim 2014). It offers three separate sets of functions called Modules that provide access to specific type of data within a watershed. These modules are watershed setup, reservoir network and simulation. The detail explanation of the model structure can be found in user's manual (USACE 2013). The HEC-DSS is a data storage system used to store and retrieve time series data.

The main inputs of HEC-ResSIM model are physical properties of Simly reservoir, reservoir operation rule curves and daily observed inflow. The physical properties of reservoir system are defined by incorporating reservoir elevation-area relationship (based on 2004 and 2013 hydrographic survey) and discharge capacity of outflow structures i.e. filtration plant and spillway. While the operational rule curves were defined by different operational and storage zones of Simly reservoir designated by CDA in HEC-ResSIM model (Figure 3.6). The operational zones (Zone-1, Zone-2 and Zone-3) are separated by two rule curves which present reservoir target levels must achieve in corresponding months. These operational zones were developed by CDA considering a full supply of 2.05 m^3/s (39 MGD) from Simly reservoir as safe yield. Figure 3.6 depicts three conditional releases based on reservoir levels, which are; (i) if reservoir level lies in Zone-1, water releases from reservoir should be at full supply of 2.05 m^3/s (39 MGD), (ii) if reservoir level lies in Zone-2, limit the supply at 1.54 m^3/s (29.25 MGD) by reducing 25% of the full supply; and (iii) if reservoir level lies in Zone-3, limit the supply at 1.025 m^3/s (19.5 MGD) by decreasing 50% of the full supply. However, Simly reservoir generally attains maximum water level (MWL) in summer monsoon, releasing surplus water through spillway with discharge capacity of 1,275 m^3/s. After input of main data, HEC-ResSIM simulated the daily reservoir levels during 2004-2013 and compared with the observed reservoir levels.

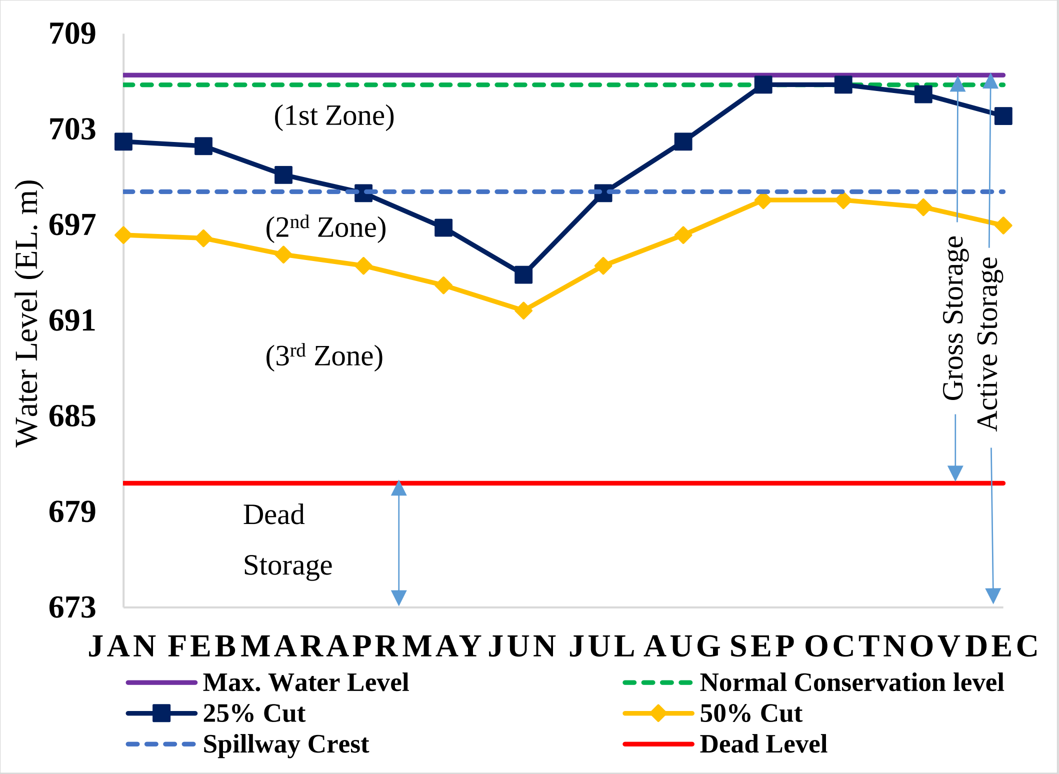


Figure 3.6 Reservoir Operational Rule Curves for Simly Reservoir.

3.4.5 Climate Change Impact Assessment

For climate change impact assessment studies, mostly researchers are using the coarse resolution general circulation models (GCMs) dataset of Coupled Model Inter-comparison Project (CMIP5) developed on the basis of Representative Concentration Pathways (RCPs). However, in current study the precipitation downscaled at fine resolution (10×10 km) which is available for 8 GCMs (4 for each of RCP8.5 and RCP4.5 scenarios) (Lutz et al. 2016) was used.

The climate change impact assessment was carried out in two steps; firstly, to study the projected changes in Simly reservoir storage under changing climate, the downscaled daily precipitation dataset of RCPs was used in HEC-HMS model after bias correction by delta approach. For future climate change investigations, the observed hydro-climatic dataset for period of 1998-2013 were used as reference hydro-climatic conditions, which is hereafter referred to as baseline (observed).

Secondly, to optimize the Simly reservoir operation strategy under changing climate, the projected inflows generated from HEC-HMS were used in HEC-ResSIM in conjunction with the current reservoir operational practices at Simly dam.

For future climate change investigations, three-time spans of 2025s (2011-2040), 2055s (2041-2070) and 2085s (2071-2100) were used in current study. The details of climate change scenarios adopted in this study are given in the following sub-sections.

3.4.5.1 Climate Change Impact Assessment on Precipitation and Storage

For a base period of 28-years (1983-2010), the monthly precipitation was extracted from IGB dataset for specific grid points at which climatic stations are located. A comparison between reference (observed) and IGB precipitation data i.e. reference (GCMs) for a base period showed large uncertainties in IGB data. Generally, all GCMs outputs contain biases (Christensen et al. 2008; Immerzeel et al. 2012) that should be corrected before impact assessment studies. Therefore, the bias correction of baseline (GCMs) precipitation data was done using delta technique to derive bias corrected baseline (GCMs) precipitation data. This simple technique has also been used in previous studies successfully (Ho et al. 2012; Immerzeel, Van Beek, Konz, Shrestha and Bierkens 2012; Teutschbein and Seibert 2012; Hawkins et al. 2013; Burhan et al. 2015) and discussed in next section. Accuracy of corrected baseline (GCMs) precipitation data was assessed and found no change between baseline (observed) and bias corrected baseline (GCMs) data as also confirmed by (Teutschbein and Seibert 2012). The future precipitation dataset for 2011-2100 comprised each individual of 8 GCMs, were corrected using the correction factor derived from baseline (observed) and baseline (GCMs) during the base period mentioned above. The projected changes in precipitation were assessed in comparison with the baseline (observed) data during different time slices (2025s, 2055s and 2085s), both for RCP8.5 and RCP4.5. Subsequently, the bias corrected RCPs daily precipitation data were utilized as input in hydrological model to project storage changes at Simly reservoir, for RCP8.5 and RCP4.5. Further, the projected storages were compared with baseline (observed) storages at Simly reservoir, represented by RCPs scenarios. The aforementioned projected changes in precipitation and storages were assessed by taking average of four GCMs belongs to each of RCP8.5 and

RCP4.5. Further, daily generated runoffs from HEC-HMS under RCP4.5 and RCP8.5, were used as input of HEC-ResSIM model to evaluate the potential impacts of climate change on Simly reservoir operational strategy.

3.4.5.2 Bias Correction of Climate Data

From data sets, daily climate data for grid boxes in which Simly and Murree station lies, was extracted using R (Programming Language) packages. For bias correction of GSMs data set, a bias correction method, determining a correction factor was applied on reference and future data sets. It is simplest method and have engaged in many studies e.g. (Ho, Stephenson, Collins, Ferro and Brown 2012; Immerzeel, Van Beek, Konz, Shrestha and Bierkens 2012; Hawkins, Osborne, Ho and Challinor 2013; Burhan, Waheed, Syed, Rasul, Shreshtha and Shea 2015).

Firstly, the monthly average and standard deviation were calculated for observed and models reference data for years (1983-2010), then correction factor for mean and variation using Equation8 and Equation9, respectively, were determined.

$$V_{Tuned} = \frac{\overline{V_{Obs}}}{\overline{V_{Ref}}} \qquad \text{Equation 8}$$

and

$$S_{Tuned} = \frac{\sigma_{Obs}}{\sigma_{Ref}} \qquad \text{Equation 9}$$

Here, V_{Tuned} is the correction factor for average, $\overline{V_{Obs}}$ is the average of observed and $\overline{V_{Ref}}$ is the average of reference data. Similarly, S_{Tuned} is the correction factor for variation, σ_{Obs} is standard deviation for observed and σ_{Ref} is standard deviation for reference data. From these two correction factors, Equation10 can be used to obtain corrected projected climate parameter V'_{Proj},

$$V'_{Proj} = \left(V_{proj} - \overline{V_{Ref}}\right).S_{Tuned} + (\overline{V_{Ref}}\,.V_{Tuned}) \qquad \text{Equation 10}$$

The correction factor obtained from baseline data was applied at each individual GCM projected data.

3.4.5.3 Climate Change Impact Assessment on Reservoir Operational Strategy

Currently mean annual water supply from Simly reservoir is 48 Mm^3 (2004-2013). To prepare future strategy, the current reservoir operational practice (i.e. the daily average water supply through filtration plant) for a period of 2004-2013 was used as baseline (S_{BL}), rather than choosing a fixed value as the case at Simly reservoir. As water demands are expected to increase in future due to demographic changes, options for better water supply plan should be investigated, therefore S_{10}, S_{30} and S_{50} scenarios with increase in baseline supply (S_{BL}) by 10, 30 and 50%, respectively, were studied.

Using HEC-ResSIM twenty-four (24) reservoir simulations were performed for 3 time slices (2025s, 2055s and 2085s) under RCP4.5 and RCP8.5, with existing operational target levels as given Figure 3.6 while changing a safe yield of 2.05 m^3/s (39 MGD) with water supply scenarios i.e. S_{BL}, S_{10}, S_{30} and S_{50} Figure 3.7. Performance of reservoir operation was evaluated in terms of water use efficiency (WUE) and RRV (reliability, resilience and vulnerability) also explained by (Hashimoto et al. 1982; Park and Kim 2014). Reliability express frequency of failure state and resilience determines that how quickly system recovers from its failure state whereas vulnerability is an indicator of extent of failure. A water use efficiency parameter tells that how much water is being efficiently used. The method and significance of these performance indices is presented in Table 3.2.

Table 3.2 Water Resources System Evaluation: Performance Indicators, Significance and Methods

Indicators (%)	**Significance**	**Methods**
Reliability	Frequency of failure states	1 – (Sum of failure states / Total number of simulated time periods)
Resilience	Speed of recovery	(Sum of restoration states) / (Sum of failure states)
Vulnerability	Extent of system failure	(Sum of water deficit) / (Sum of water demand during failure states)
Water Use Efficiency	Supply through filtration plant	(Sum of water released through the filtration plant) / (Sum of water inflow into the reservoir)

Here, the system is defined as in failure, when it is unable to provide planned water supply. These commonly used performance indices for water resources projects are in next sections.

It is quite possible that the existing operational target levels may not remain feasible for all water supply scenarios under changing climate for all time slices mentioned above. In that case, further possibilities were explored by modifying the current operational strategy (i.e. existing operational target levels). By hit and trail approach, target levels were modified and reservoir simulations were performed for each of the modified target levels with the aim to improve overall system performance under changing climate. The process was repeated until system attains its maximum reliability with fair resilience, good water use efficiency and least vulnerability. While modifying the operational target level, a special care was also considered that conservation level of reservoir should be attained at least once in the year.

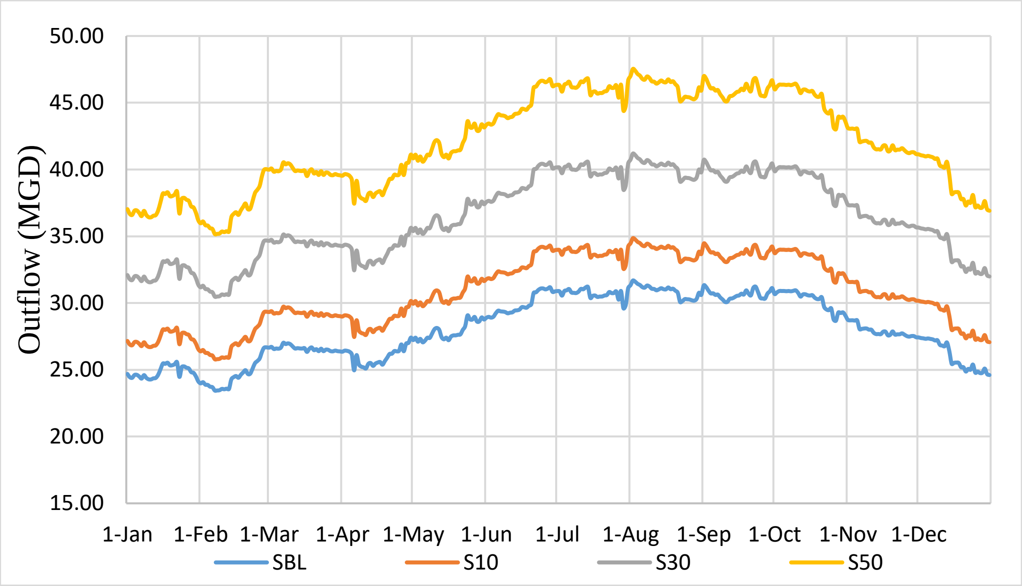


Figure 3.7 Water supply plans through filtration plant from Simly reservoir.

3.4.5.4 Reliability

Reliability is defined as the probability of the system being in a satisfactory state. Denote the state of system by random variable Xt at time t, where t takes on discrete values 1, 2, ..., n. Then the possible Xt values can be partitioned into two sets: S, the set of all satisfactory outputs, and F, the set of all unsatisfactory outputs. The reliability of the system can be expressed as Eq. 11

$$\alpha = P\{X_t \in S\} \qquad \text{Equation 11}$$

For a water supply system, a failure is said to have occurred when supply is less than the demand. Therefore, the reliability is the ratio of non-failure periods to total periods in the operating horizon.

3.4.5.5 Resilience

Resiliency describes the capacity of a system to return to a satisfactory state from a state of failure. Mathematically, it can be represented as **Error! Reference source not found.** (Park and Kim 2014),

$$Resilience = \frac{\text{Sum of restoration states}}{\text{sum of failure states}} \qquad \text{Equation 12}$$

3.4.5.6 Vulnerability

Even though the probability of failure of a system may be very low, it is necessary to examine the damage due to a possible failure. In real situation, few systems can be made so large or so safe that failures are impossible and even when it is possible to provide such a level of security, the cost is likely to be prohibitive. Logically then, efforts should be made to ensure that the damages by a failure are not severe. The vulnerability is an important criterion to describe the severity of failure for a system.).

$$Vulnerability = \frac{\text{Sum of water deficit}}{\text{sum of water demand during failure states}} \qquad \text{Equation 13}$$

3.4.5.7 Water Use Efficiency

Water use efficiency is simply obtained by dividing sum of water released through filtration plant by sum of water entered in the reservoir.

Chapter 4

RESULTS AND DISCUSSION

4.1 LAND USE CHANGES

Using the ERDAS Imagine, land use maps of Simly catchment were prepared for year 2004 and 2013 as shown in Figure 4.1.

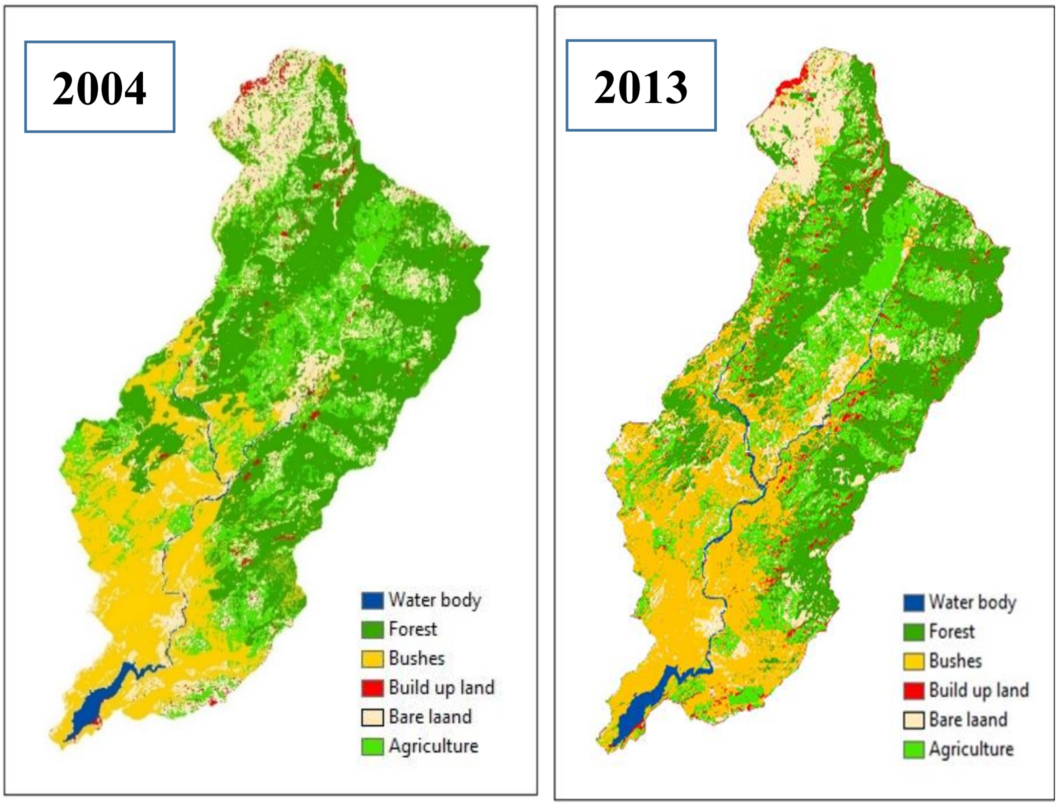


Figure 4.1 Land Use Map of Simly Dam Catchment

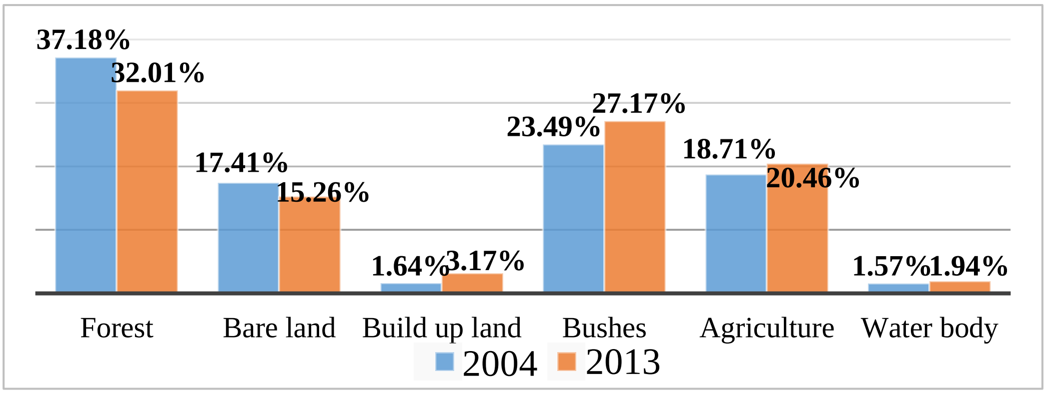


Figure 4.2 Histogram of land use Changes occurred from year 2004 to 2013.

Maps reveal that the catchment is mostly covered with forest and bushes. Histograms presented in Figure 4.2 provide a better understanding to explore the changes experienced in the catchment from year 2004 to 2013. The major change is observed in forest covered area, which was 37.18% of total catchment area in 2002 and surprisingly contracted to 32.01% in 2013. Another decreasing trend is observed for bare land from 17.41% to 15.26%. 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 which is considered as most influencing element to change the hydrological behavior (Schultz 1995; Ali, Khan, Aslam and Khan 2011; Suriya and Mudgal 2012) is almost doubled in these twelve years from 1.64% to 3.17%. It can be used as a hint to consider a population increase in the catchment (Zeug and Eckert 2010). In other classes, agricultural land increased from 18.71% to 20.46%, bushes from 23.49% to 27.17% and water body with very minimal change from 1.57% to 1.94%.

4.2 HYDROLOGICAL MODELLING

From ensemble of initially selected 12 combinations of different methods are presented in Table 4.1. with statistical performance test results and these methods represent different hydrological processes. It is found that bounded recession base flow method happens with poor results with any combination of set of methods. However, constant monthly base flow and recession method provides satisfactory results. SCS loss method results are far from acceptance. For this study, it is found that a set of methods consist of deficit and constant loss method for losses calculation, simple surface method, constant monthly base flow, SCS unit hydrograph for transformation, and Muskingum routing method for river routing, provide best results as compare to any other set of combination. The statistical performance evaluation test results for complete run of calibration and validation period lie in acceptable range. Nash-Sutcliff coefficient is found as 0.845 for calibration and 0.8194 for validation periods. Root mean square error (RMSE) results into 1.98 and 2.45 for calibration and validation period respectively. The coefficient of determination is 0.84 and 0.83 for calibration and validation period.

Table 4.1 Result Summary of HEC-HMS Performance for Twelve Different Methods

Results Summary, [Calibration (2004-2007)] & [Validation (2011-2013)]									
Methods				**Results (Daily Inflow)**					
Base flow Method	**Loss Method**	**Transform Method**	**Routing Method**	**Nash-Sutcliffe**		**RMSE**		**R²**	
				Calibration	**Validation**	**Calibration**	**Validation**	**Calibration**	**Validation**
Constant Monthly	Deficit & Constant	SCS Unit Hydrograph	Muskingum	**0.8456**	**0.8194**	**1.98**	**2.33**	**0.84**	**0.83**
Constant Monthly	Deficit & Constant	Clark Unit Hydrograph	Muskingum	0.734	0.582	2.4	3.2	0.74	0.61
Constant Monthly	Initial & Constant	SCS Unit Hydrograph	Muskingum	**0.827**	**0.772**	**1.9**	**2.4**	**0.80**	**0.78**
Constant Monthly	SCS	SCS Unit Hydrograph	Muskingum	-6.134	-5.145	12.5	12.4	0.53	0.62
Recession Base Flow	Deficit & Constant	SCS Unit Hydrograph	Muskingum	**0.823**	**0.7817**	**2**	**2.4**	**0.78**	**0.78**
Recession Base Flow	Deficit & Constant	Clark Unit Hydrograph	Muskingum	0.732	0.578	2.4	3.3	0.72	0.61
Recession Base Flow	Initial & Constant	SCS Unit Hydrograph	Muskingum	**0.823**	**0.7817**	**2**	**2.4**	**0.78**	**0.78**
Recession Base Flow	SCS	SCS Unit Hydrograph	Muskingum	-6.171	-5.14	12.5	12.4	0.53	0.62
Bounded Recession	Deficit & Constant	SCS Unit Hydrograph	Muskingum	0.7666	0.35	2.3	4	0.78	0.57
Bounded Recession	Deficit & Constant	Clark Unit Hydrograph	Muskingum	0.676	0.305	2.7	4.2	0.72	0.51
Bounded Recession	Initial & Constant	SCS Unit Hydrograph	Muskingum	0.7666	0.35	2.3	4	0.78	0.57
Bounded Recession	SCS	SCS Unit Hydrograph	Muskingum	-5.602	-0.813	12	6.7	0.53	0.57

The parametric values of finally selected methods for hydrological assessment of Simly dam Catchment are presented in Table 4.2.

Figure 4.3 show observed and HEC-HMS simulated daily inflow into reservoir for calibration and validation periods, respectively. For both periods, HEC-HMS model has managed to simulate high and low peaks very well rather than a very few ones, where HEC-HMS calculations are underestimated. But overall model performance indicates that a strong correlation exists between observed and HEC-HMS simulated inflows.

Table 4.2 Calibrated Sub-Basin Wise Parametric Values for HEC-HMS Model, Simly Catchment

Parameters	**Sub-basins**		
	1	**2**	**3**
Initial Storage, I_s (mm)	4	4	4
Maximum Storage, M_s (mm)	6	7	5
Initial Deficit, I_d (mm)	2	2	2
Maximum Deficit, M_d (mm)	24	24	24
Constant Rate, C_r (mm/hr)	1.3	1.35	1.22
Impervious, I_m (%)	8	6	6
Curve Number, *CN*	73	71	78
Lag Times, t_{lag} (min)	89	75	83
River			
Muskingum *K* (hr)	1.4		
Muskingum *X*	0.35		

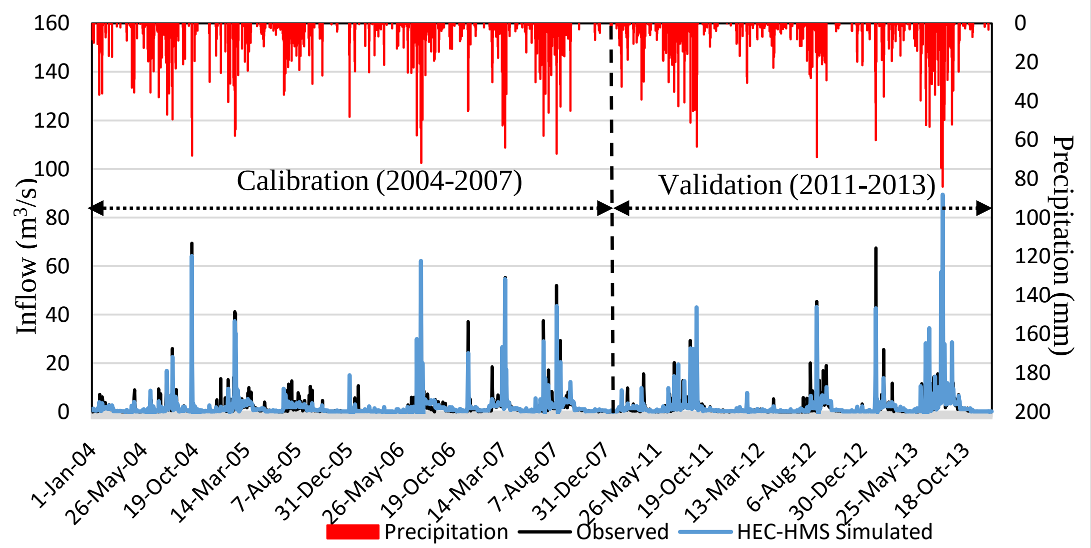


Figure 4.3 Observed and HEC-HMS simulated daily inflow into Simly reservoir.

Figure 4.4 graphically represent a comparison of reservoir levels calculated by HEC-HMS and observed readings. The model results match very well with observed readings and can be used for further investigations.

Figure 4.5 show scattering of simulated inflows against observed inflows for both calibration and validation and show a strong correlation between modelled and observed values. The NS coefficient is 0.829, RMSE is 2.073 and R^2 is 0.8336.

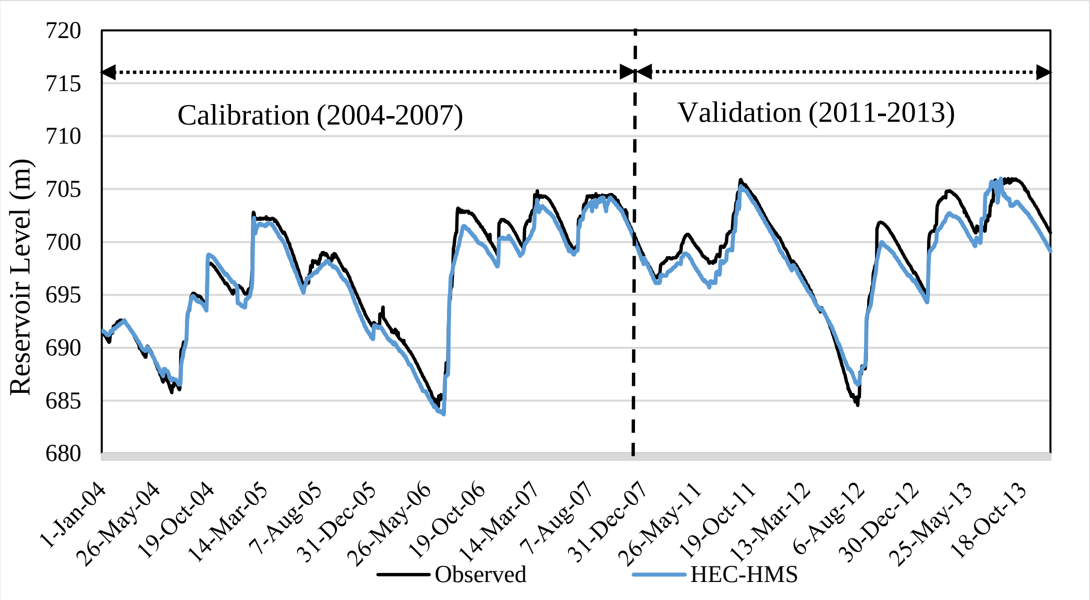


Figure 4.4 Observed and HEC-HMS simulated daily reservoir level at Simly reservoir

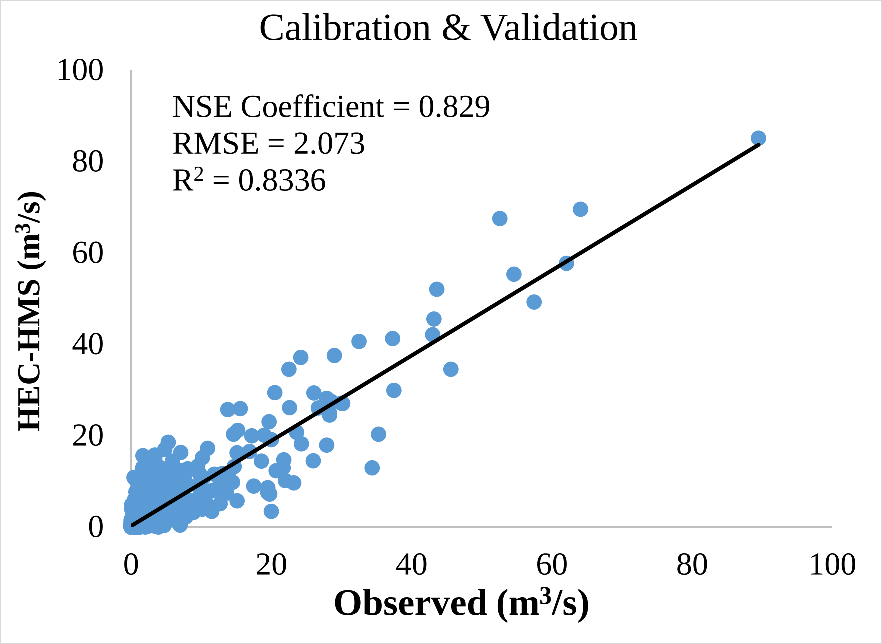


Figure 4.5 Scattering of Observed & HEC-HMS Simulated Inflow

The performance of the model at seasonal basis is presented in Table 4.3. Here, the seasons are defined as winter, spring, summer, monsoon and autumn. It is found that model lack its performance for summer season to simulate flows but is in acceptable range. Also, summer does not happen as period of high flows. Monsoon months are wet months and most of the high flows occur in this season and model performance for these months is in acceptable range. Unlike to summer, model's performance for winter, spring, monsoon and autumn is in fair range and acceptable for further simulations.

Table 4.3 Summary of HEC-HMS performance at Seasonal basis.

Time (Season)	Ns		RMSE		R^2	
	Calibration	Validation	Calibration	Validation	Calibration	Validation
Winter (Nov-Feb)	0.81	0.87	1.78	1.84	0.79	0.86
Spring (Mar-Apr)	0.94	0.62	1.19	1.70	0.94	0.63
Summer (May-Jun)	0.60	0.68	1.04	1.31	0.64	0.76
Monsoon (Jul-Aug)	0.80	0.80	3.49	4.43	0.80	0.84
Autumn (Sep-Oct)	0.89	0.80	1.56	2.04	0.89	0.83
Annual	0.85	0.82	1.98	2.34	0.84	0.83

4.3 RESERVOIR SYSTEM SIMULATIONS

HEC-ResSIM model was run to simulate reservoir level using observed inflow and original operational rule curves for 2.05 m^3/sec and results are presented in Figure 4.6. As model is developed to determine a water release, keeping reservoir level in targeted range as assigned in operational rule curves and a considerable difference between observed and simulated reservoir levels is observed. The variability in annual sum of releases is resulted as RMSE = 12.6 Mm^3 and R^2 = 0.63 during calibration (2004-2010) and RMSE = 6.11 Mm^3 and R^2 = 0.63 during validation (2011-2013). While comparing these levels, several factors are needed to consider e.g. violation of operational control rules and uncertainty of flow data.

The flow duration curve Figure 4.6 (c) explain comparison of observed and HEC-ResSIM simulated filtration releases for a period of 2004-2013. It can be noticed that in past years, amount of 2.05 m^3/sec water was just supplied for a short percent of time (less than 10%). While HEC-ResSIM simulations inform that by following operational rule curves supplies of 2.05 m^3/sec could be possible for 48% of time but on other hand zero supply situations could also had to face.

It can be deduced that either rule curve was not strictly followed in past years or 2.05 m^3/sec is not correctly defined in rule curve.

Figure 4.6 Comparison of Observed and HEC-ResSIM Simulated a) Daily Reservoir Level, b) Annual Release (Filtration + Spillway), c) Flow Duration Curve of Daily Filtration Suppl

4.4 FREQUENCY ANALYSIS OF PRECIPITATION EVENTS

Frequency analyses were aimed to find out best fit distribution for study's catchment and to estimate rainfall intensity for given return period. A best fit distribution is also a useful tool to compare present and future trend of precipitation. Initially, Normal, Log-Normal and General Extreme Value 1 (Gumbel) distributions were applied for two gauging stations Murree and Simly. Figure 4.7 shows scattering of data against reduced variate of Normal, Log-Normal distribution and Gumbel distribution for Murre and Simly rainfall station.

Table 4.4 summarize the results of goodness of fit test and statistically prove that Log-Normal distribution is best fit distribution for both stations. Chi-Squared test statistics 2.1851 for Murree and 0.02921 for Simly station, whereas (R^2) value 0.96 for Murree and 0.912 for Simly ranks the Log-Normal distribution as best fit distribution. Gumbel distribution may be used as second choice for Simly station if necessary, but at Murree station any other distribution rather than Log-Normal is uncertain. However, Normal distribution is not suggested to apply for any frequency analysis, on basis of present analyses.

Table 4.4 Goodness of fit test results for probability distributions applied at Murree and Simly station.

Probability Distribution	**Murree**		**Murree**	**Simly**		**Simly**
	Chi-Squared (X^2)		**(R^2)**	**Chi-Squared (X^2)**		**(R^2)**
	Statistics	**Rank**		**Statistics**	**Rank**	
Normal	7.04	2	0.87	2.06	3	0.75
Log-Normal	2.18	1	0.96	.03	1	0.91
Gumbel	9.75	3	0.95	.09	2	0.82

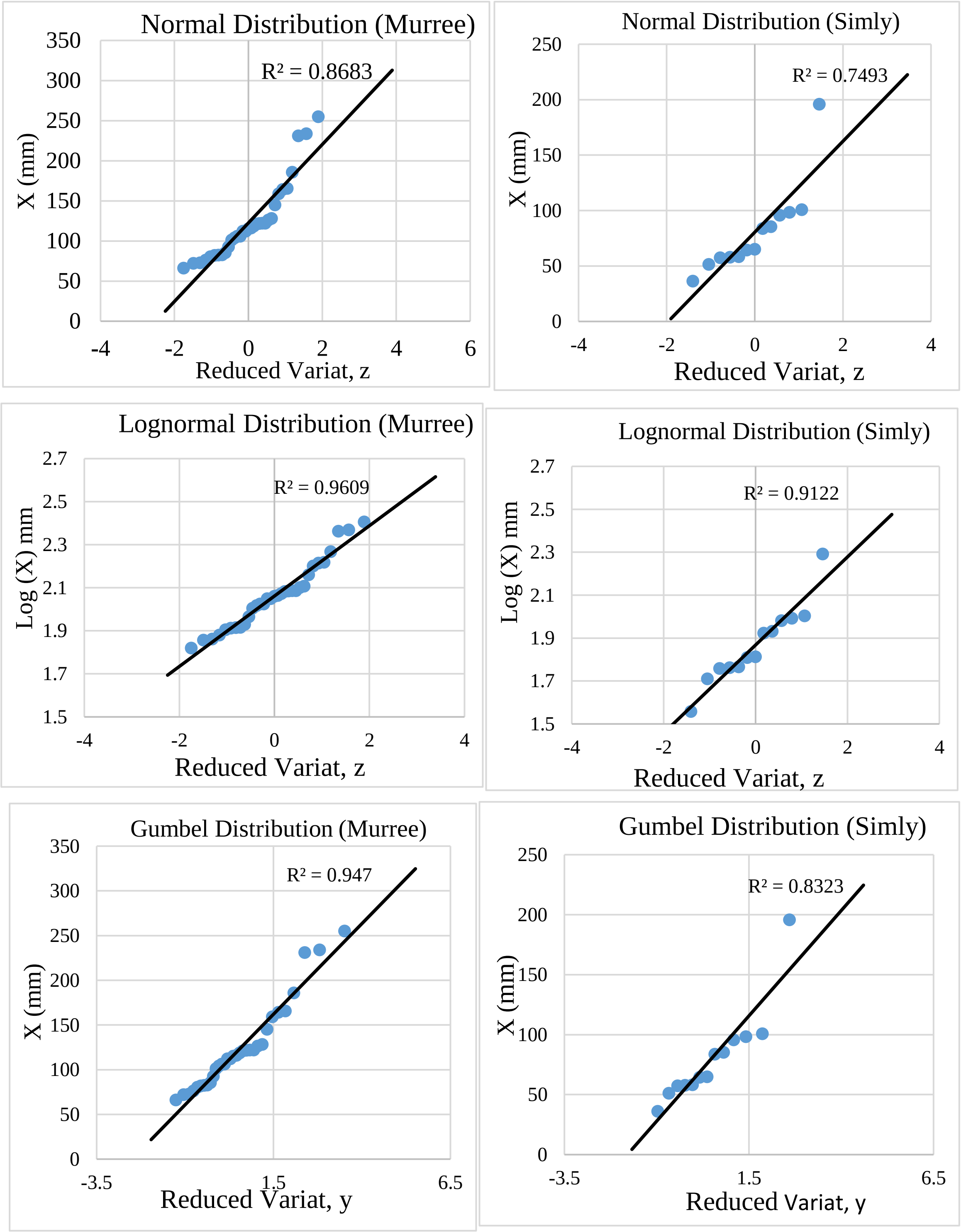


Figure 4.7 Plotting of data against reduced variate for Normal, Log-Normal and Gumbel distributions

Figure 4.8 *(a)* & *(b)* represents return period of 24hr maximum rainfall events through Log-Normal distribution with 90% confidence level, for Murree and Simly station respectively. Murree station seems to be more susceptible for high intensity precipitation events than Simly one.

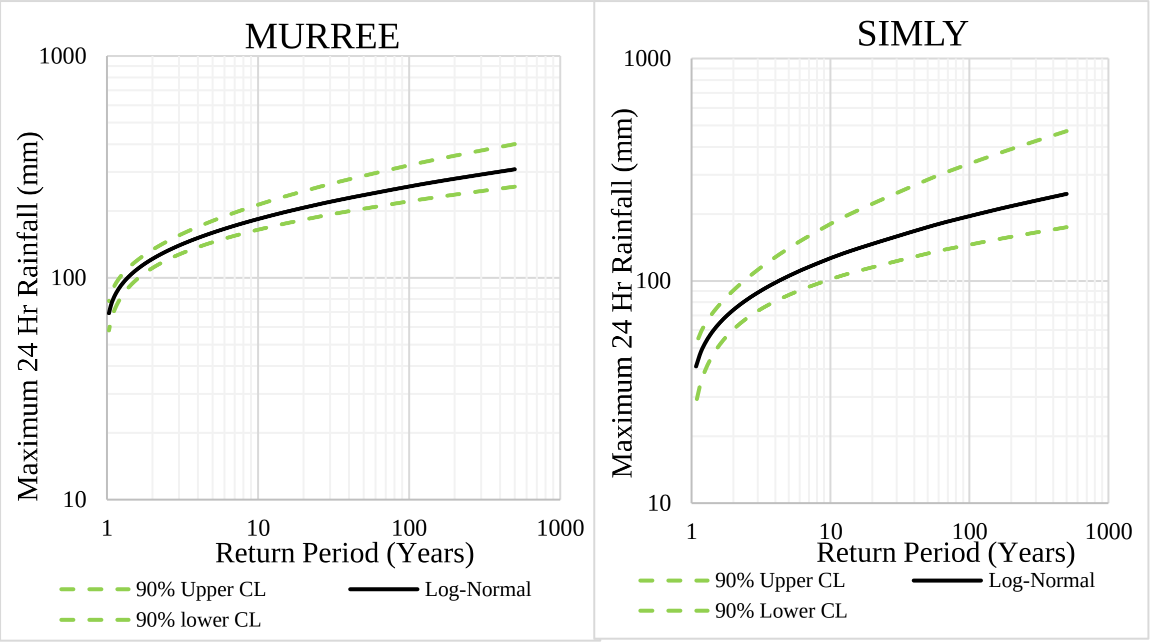


Figure 4.8 Log-Normal distribution for a) Murree station, b) Simly station

HEC-HMS was applied with initial reservoir level at 699.69 m to check hydrological response of the catchment and reservoir capacity to spill surplus water from spillway to define sustainability of dam structure and saving from overtopping against rainfall events of 2, 5, 10, 50, 100 and 500 years return period. For simulations, it is assumed that same return period rainfall event occurs on both stations, simultaneously. Figure 4.9 explains that spillway safely passed out surplus water, even in case of 500 years return period.

4.5 CLIMATE CHANGE IMPACT ASSESSMENT

4.5.1 Bias Correction

Figure 4.10Figure 4.10 shows a comparison of reference data before and after bias correction with observed data, for both stations Murree and Simly. 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.

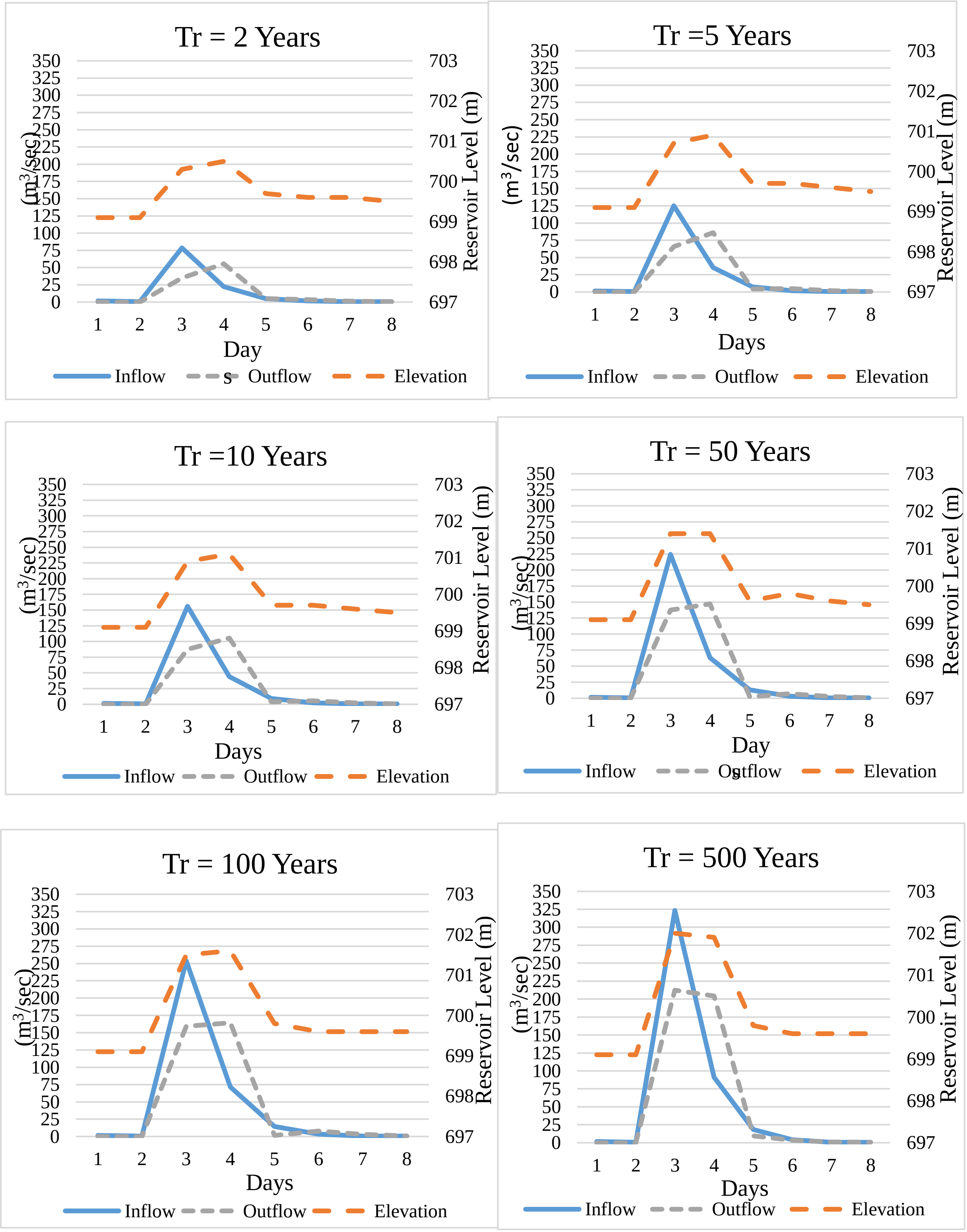
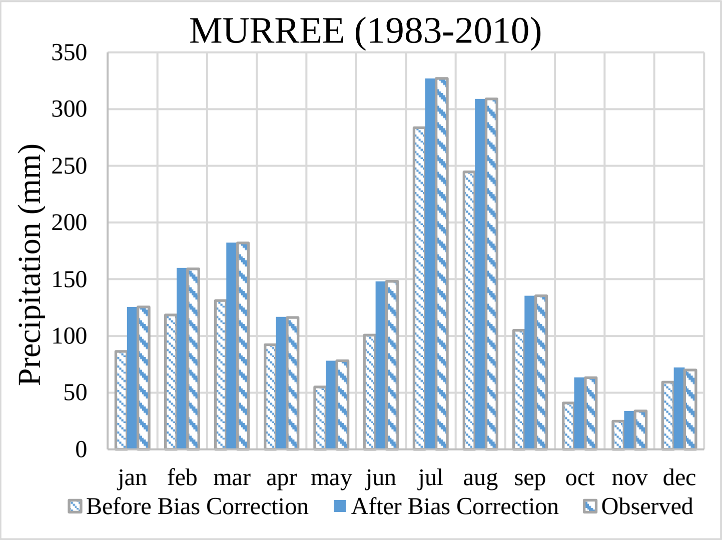
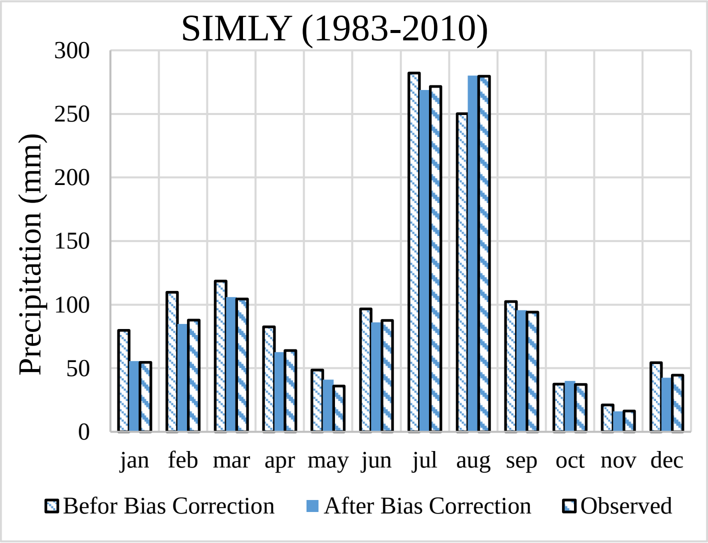


Figure 4.9 HEC-HMS Simulated Inflows, outflows and reservoir levels at Simly reservoir against rainfall events of different return period



(a)



(b)

Figure 4.10 Comparison of mean monthly observed and bias corrected precipitation from 1983-2010. a) Murree, b) Simly

4.5.2 Climate Change Impacts on Precipitation

Figure 4.11 & Figure 4.12 depicts a changing trend of precipitation for each month of the year under emission scenarios RCP8.5 and RCP4.5 from current climate (1998-2010) to end of the century for Murree and Simly stations, respectively. The selection of years for current climate representation is done for the same years of data available for inflow. It is perceived that baseline for precipitation and Inflow of same years is useful for rainfall-runoff comparison purposes.

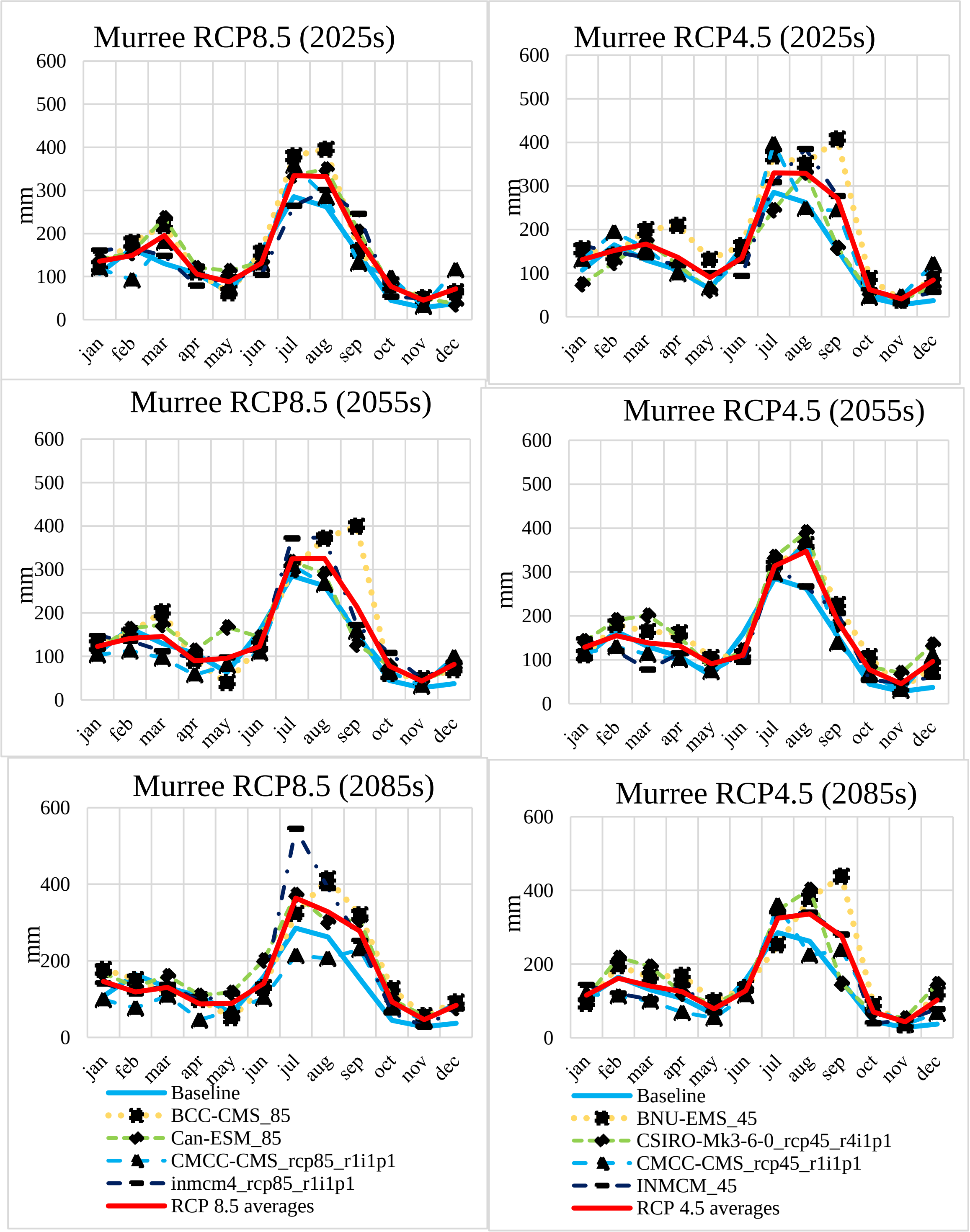


Figure 4.11 Projected changes in precipitation at Murree station.

At Murree station, in Figure 4.11, under RCP8.5 (left side), 4 models average line almost follow the same trend as under current climate (Baseline) condition with a positive change. However individual behavior of bcc-csm1-1_rcp85_r1i1p, and inmcm4_rcp85_r1i1p1 is different. bcc-csm1-1_rcp85_r1i1p output show positive trend throughout the century with a significant change in climate shifting from July and August to August and September for 2055s. inmcm4_rcp85_r1i1p1 seems to predict less precipitation as compare to other models for 2025s and a considerable increase for month of July is forecasted in 2085s. CMCC-CMS_rcp45_r1i1p1 predicts less precipitation for July and August and greater for September as compare to baseline for 2085s. For RCP4.5 scenario 4 models average curve presents increase in precipitation especially from July to September. Individual behavior of the models is different from each other. BNU_EMS_45 predicts September as most wet month of the year for near future 2025s and far future 2085s.

For Simly station, Figure 4.12, bcc-csm1-1_rcp85_r1i1p, and inmcm4_rcp85_r1i1p1 behavior is similar as in case of Murree. CMCC-CMS_rcp85_r1i1p1 presents entirely different scenario from other models for 2085s with a surprisingly decreasing trend far from average especially July-August.

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 4.5 explain the predictions of precipitation under RCP4.5 and RCP8.5 at seasonal and annual bases and their variation from baseline for Murree and Simly station. Table 4.6 present projected change in averagely distributed precipitation in the Simly dam catchment.

Seasons are defined here as winter (Nov-Feb), Spring (Mar-Apr), Summer (May-Jun), Monsoon (July-Aug) and Autumn (Sep-Oct).

Generally, there is increase in precipitation for both scenarios at both station, so same results are found for averagely distributed precipitation over the whole catchment Table 4.5 and Table 4.6. By taking average of ensembles of models for RCP4.5 and RCP8.5 show that for near future (2025s) both scenarios cause to increase in precipitation from baseline. RCP4.5 is comparatively scenario of greater precipitation with 23.2% increase compare to RCP8.5 with 18.13% increase, annually average, for 2025s. For 2055s annual increase is 15.05% & 16.20%, and for 2085s increase is 22.74% and 21.64% under RCP8.5 and RCP4.5, respectively. Forecasting till at the end of century informs that for both scenarios, increase in precipitation is less for mid future 2055s than 2025s and 2085s.

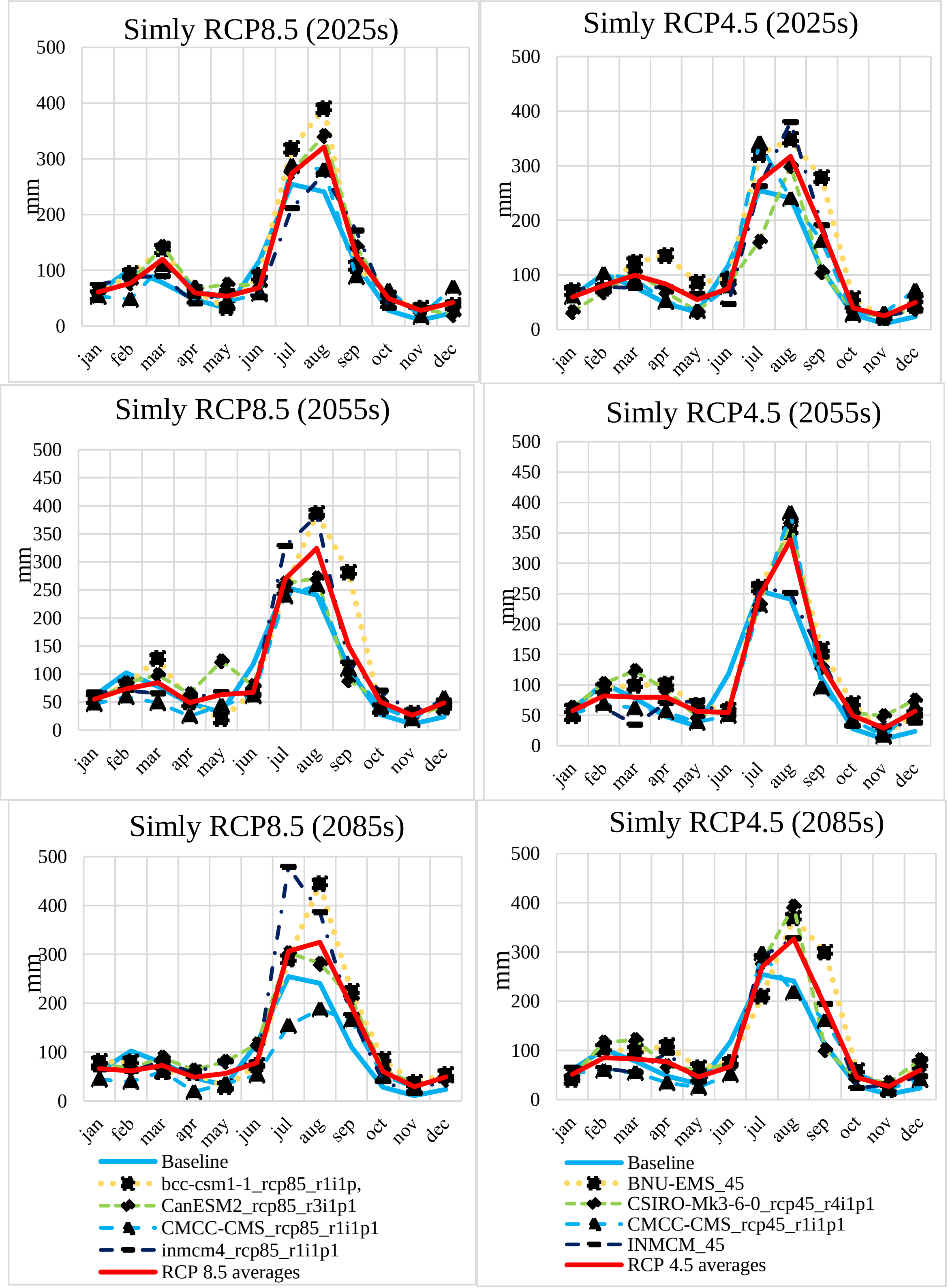


Figure 4.12 Projected changes in precipitation at Simly station.

Table 4.5 Seasonal variation in precipitation at Murree and Simly station.

	Season	**Murree Precipitation (mm)**				**Simly Precipitation (mm)**			
		RCP8.5		**RCP4.5**		**RCP8.5**		**RCP4.5**	
		Absolute	**Deviation**	**Absolute**	**Deviation**	**Absolute**	**Deviation**	**Absolute**	**Deviation**
2025s	**Winter**	401	56	408	64	209	-19	216	-12
	Spring	302	75	303	76	180	73	183	76
	Summer	219	-2	224	4	123	-28	130	-20
	Monsoon	667	112	659	104	596	90	589	83
	Autumn	263	74	334	145	177	62	224	109
	Annual	1851	316	1928	393	1285	178	1342	235
2055s	**Winter**	390	46	426	81	204	-24	225	-3
	Spring	236	9	270	44	134	27	160	52
	Summer	219	-1	201	-19	131	-19	111	-39
	Monsoon	650	95	661	106	594	88	585	79
	Autumn	292	103	265	76	200	85	182	67
	Annual	1788	252	1822	287	1263	156	1263	156
2085s	**Winter**	396	51	424	79	206	-22	224	-4
	Spring	219	-8	266	39	121	14	159	52
	Summer	230	10	207	-14	135	-16	113	-37
	Monsoon	692	137	660	106	631	125	596	90
	Autumn	370	181	346	157	254	138	234	118
	Annual	1907	371	1902	366	1348	241	1326	219

Baseline (1998-2013)	**Murree (mm)**	**Simly (mm)**
Winter (Nov-Feb)	345	228
Spring (Mar-Apr)	227	107
Summer (May-Jun)	220	150
Monsoon (Jul-Aug)	555	506
Autumn (Sep-Oct)	189	115
Monthly Avg.	1536	1107

Inter-annual change is much fascinating with gradual decrease for spring season from 2025s to 2085s under both emission scenarios. Summer season is predicted as drier for 2025s for both RCPs and at end of century it is predicted that under RCP4.5 summer will be drier as compare to RCP8.5.

Table 4.6 Seasonal Change in averagely Distributed Precipitation in the Simly Dam Catchment

	Season	Basin Avg. Precipitation (mm)			
		RCP8.5		RCP4.5	
		Absolute	Deviation	Absolute	Deviation
2025s	**Winter**	293	14	300	21
	Spring	233	74	236	76
	Summer	165	-16	171	-10
	Monsoon	627	99	620	92
	Autumn	215	67	272	125
	Annual	1533	238	1599	304
2055s	**Winter**	285	6	313	34
	Spring	179	19	208	49
	Summer	170	-11	150	-31
	Monsoon	619	91	618	91
	Autumn	241	93	218	71
	Annual	1493	198	1508	213
2085s	**Winter**	290	10	311	32
	Spring	164	4	206	47
	Summer	177	-5	154	-27
	Monsoon	658	131	624	97
	Autumn	305	157	283	135
	Annual	1593	298	1579	284

Baseline (1998-2013)	Basin Average (mm)
Winter (Nov-Feb)	279
Spring (Mar-Apr)	160
Summer (May-Jun)	181
Monsoon (Jul-Aug)	528
Autumn (Sep-Oct)	148
Monthly Avg.	1295

4.5.3 Climate Change Impact assessment on storage

To predict a change in inflow volume of water into reservoir, observed daily rainfall data was replaced with climate models projected data in calibrated and validated HEC-HMS model.

Figure 4.13 show projected inflows under RCP8.5 and 4.5 emission scenarios. It provides information to understand behavior of individual model and average of 4 GCMs under each emission scenarion. Under RCP8.5 (Left side) individual models show similar trend for 2025s and 2055s time windows except BCC-CSM_85. For 2085s time window INMCM_85 predicts July as wettest month of the year unlike to other models.

Under RCP4.5 (Left side) there are not any major shift of flow pattern and trend is apparently same as baseline. For 2085s, it can be seen that CSIRO_MK3-6-0_rcp45 predict a very considerable increase in flow compare to other models.

Here, it is being considered that average of models, categorized on basis of emission scenarios, may lead to better understanding of future water availability.

However, Table 4.7 is developed to present future water availability for aforementioned five seasons and annual average. Results show that maximum inflow will be available in monsoon season. It is vital period of the month to store surplus water in order to facilitate to protect water supplies rest of the year. Here, reservoir operational capacity plays a critical role. Here, it is worth noting that selection of water supply amount will largely depend on operational and storage capacity of the system, not only on inflow increases or decreases.

Summer is projected as the period of very low flows comparing to other seasons, from near future to far future. Prediction of increase in flows for autumn is comparatively greater than other seasons. This increase is largely affected by contribution of month of September as part of post monsoon. Increase in flow for these months of the year hints that importance of reservoir operational capacity and strategy will increase considerably in future.

It can also be noticed that increase in precipitation for month of September yields more volume of water.

This is the reason; tendency of increasing inflow volume is larger for autumn season as compare to other seasons. It may also be explained by introducing a prediction of increase in extent of monsoon flows in future.

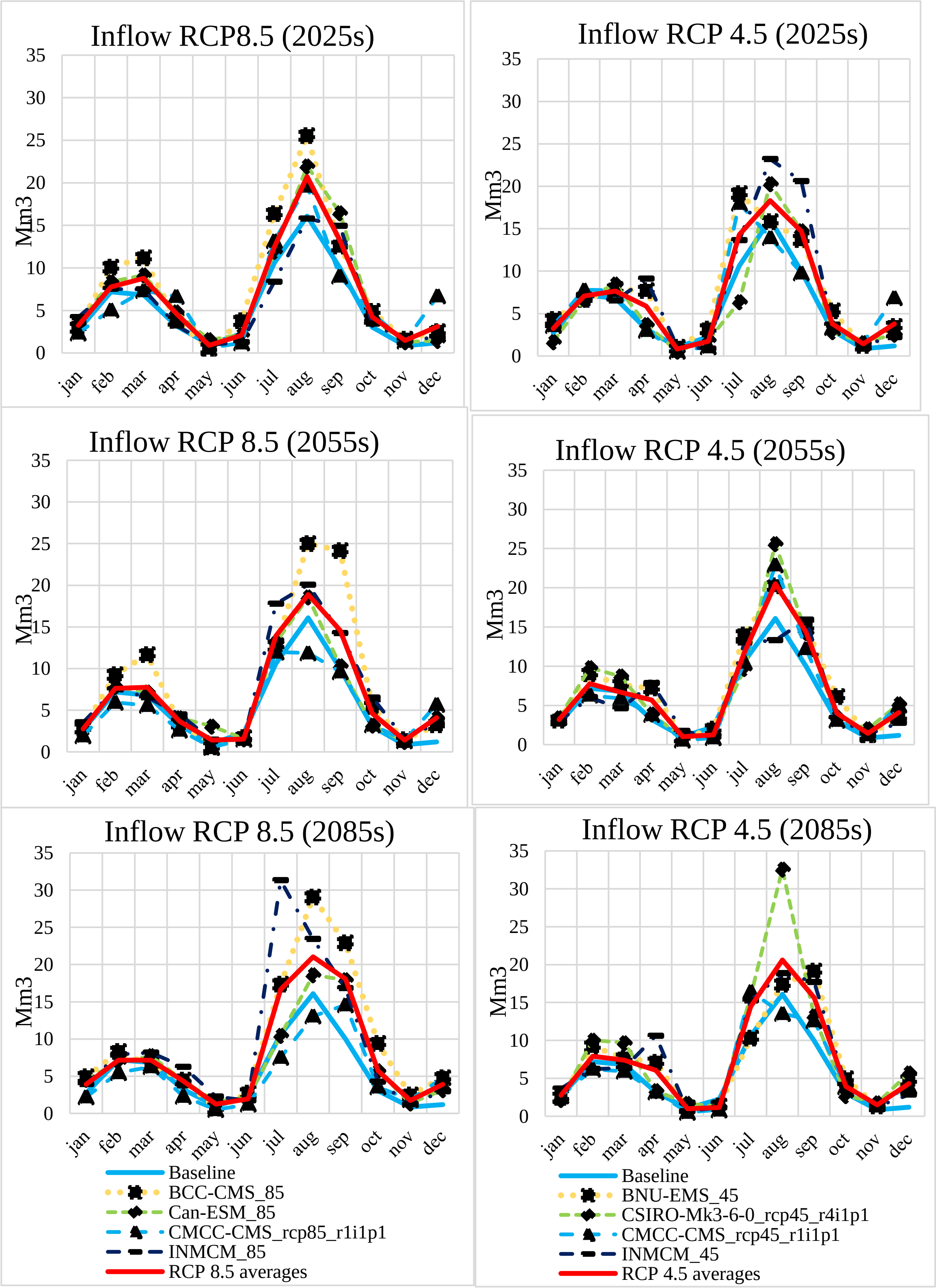


Figure 4.13 Climate change impacts on storage at Simly reservoir.

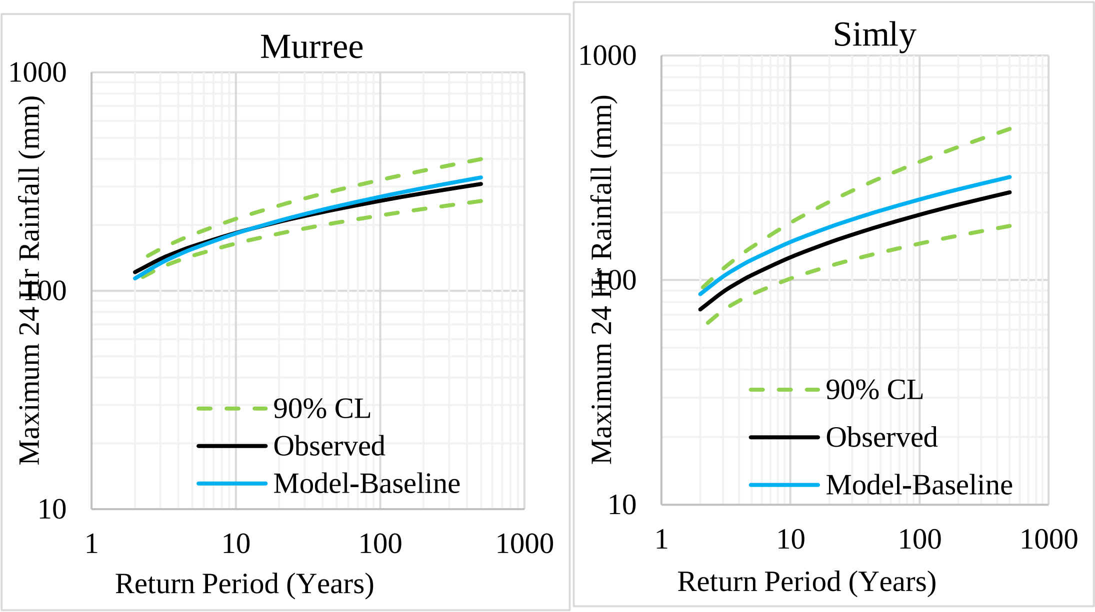
Table 4.7 Seasonal Variation in Storage at Simly reservoir under Climate Change

	Season	**Inflow (Million m3)**			
		RCP8.5		**RCP4.5**	
		Absolute	**Deviation**	**Absolute**	**Deviation**
2025s	**Winter**	15.6	3.0	15.5	3.0
	Spring	13.4	4.3	13.5	4.4
	Summer	3.0	-0.3	2.6	-0.7
	Monsoon	33.2	5.8	32.6	5.2
	Autumn	17.5	5.9	18.5	6.9
	Annual	82.7	18.8	82.7	18.8
2055s	**Winter**	15.9	3.3	16.5	3.9
	Spring	11.4	2.3	12.4	3.3
	Summer	3.0	-0.3	2.3	-1.0
	Monsoon	32.8	5.4	32.3	4.9
	Autumn	19.2	7.6	18.4	6.8
	Annual	82.3	18.4	81.8	17.9
2085s	**Winter**	16.7	4.1	16.5	3.9
	Spring	11.5	2.4	13.5	4.4
	Summer	3.2	-0.1	2.1	-1.1
	Monsoon	37.7	10.3	35.1	7.7
	Autumn	23.7	12.2	19.6	8.0
	Annual	92.8	28.9	86.8	22.9

Baseline (1998-2013)	**Inflow**
Winter (Nov-Feb)	13
Spring (Mar-Apr)	9
Summer (May-Jun)	3
Monsoon (Jul-Aug)	27
Autumn (Sep-Oct)	12
Annual Avg.	64

4.5.4 Impacts of Climate Change on Frequency of Precipitation

Regarding to projected changes in frequency of precipitation events, we are just focused to change in frequency of high intensity precipitation events and its consequences on Simly reservoir. For this purpose, Log-Normal frequency distribution was applied for baseline (1983-2010) and projected data series for 2025s, 2055s and 2085s time windows. Data sample was consisting of 30 readings, one for each year, having maximum rainfall for 24 Hr duration. Results show that for same return period, magnitude of 24-hr maximum rainfall derived by baseline data of climate models is very close to the frequency curve derived by observed data at Murree station. For Simly station, it also lies in the 90% confidence limit of observed frequency curve Figure 4.14.



(a) (b)

Figure 4.14 Log-Normal distribution for observed station data and bias corrected climate models reference data, a) Murree station, b) Simly station

Comparing to current climate, future predictions of occurrence of extreme rainfall events is substantially very high for some GCMs Figure 4.15. It is worth noted that increasing frequency of extreme rainfall events is certain under both scenarios and all models. This change is extraordinary for 2085s compare to 2025s. Outcomes assure that there is not any signal to consider a decreasing trend of extreme events.

HEC-HMS model was run against 200 & 500 years return period precipitation for all models and future time slices (2025s, 2055s & 2085s) and found that spillway have capacity to spill the water safely. Anyhow, from management point of view, increasing frequency of high intensity events is a serious concern and enacted to spill precious amount of water through spillways.

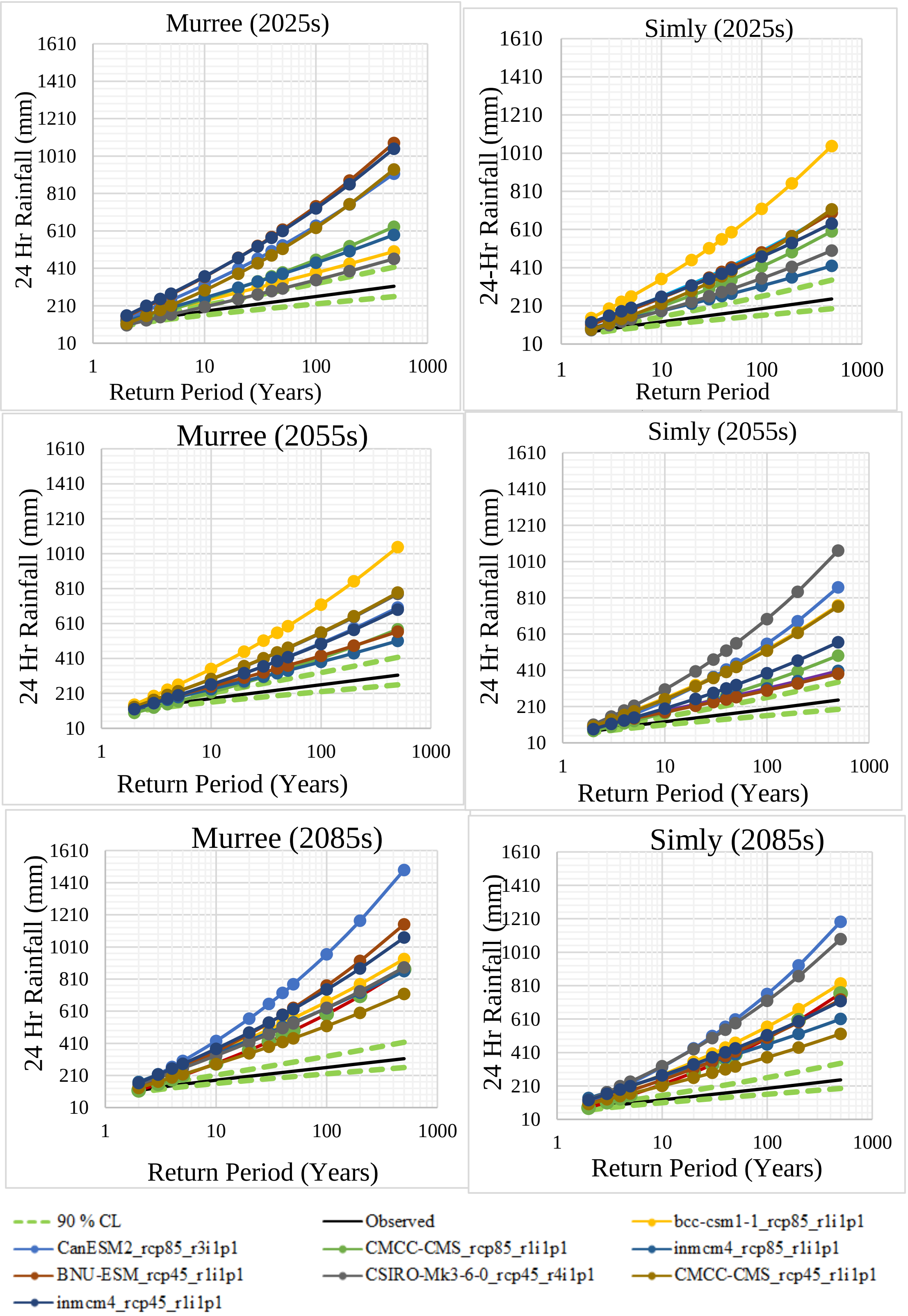


Figure 4.15 Climate change impacts on frequency of 24-hr duration maximum rainfall at Murree (left) and Simly (Right) climate station.

4.5.5 Climate Change Impacts on Reservoir Operational Strategy

One of the main objective of this study was to assess potential impacts of climate change on Simly reservoir operational strategy. For this purpose, HEC-ResSIM model was applied to simulate water levels from 2011-2100 using HEC-HMS simulated flows under future climate change scenarios. Performance of the system, was assessed in terms of reliability, resilience, vulnerability and water use efficiency, against four water supply plans S_{BL}, S_{10}, S_{30} & S_{50} and current water level targets.

Table 4.8 & *Table 4.9* explains that performance of system in term of reliability, resilience, vulnerability and water use efficiency.

Table 4.8 Comparison of performance of present and modified rule curve under RCP8.5.

	2011-2040 (2025s)							
Emission Scenario	RCP8.5							
Supply	S_{BL}		S_{10}		S_{30}		S_{50}	
Operational Rule	Present	Modified	Present	Modified	Present	Modified	Present	Modified
Reliability%	99.59	99.64	98.50	99.02	89.22	98.36	79.89	92.11
Resilience%	53.33	53.85	34.76	28.97	19.22	38.89	6.62	16.32
Vulnerability %	63.83	59.55	56.73	54.59	45.14	50.82	49.29	51.58
W.Use Efficiency %	49.63	49.66	54.28	54.44	61.54	64.12	67.20	71.47
	2041-2070 (2055s)							
Emission Scenario	RCP8.5							
Supply	S_{BL}		S_{10}		S_{30}		S_{50}	
Operational Rule	Present	Modified	Present	Modified	Present	Modified	Present	Modified
Reliability%	99.74	99.74	98.46	99.16	90.40	99.09	80.86	97.51
Resilience%	67.86	67.86	41.42	33.70	20.53	48.00	7.15	19.41
Vulnerability %	59.20	59.20	44.68	36.57	39.22	53.66	47.87	67.06
W.Use Efficiency %	47.97	47.97	52.49	52.51	60.10	61.91	65.42	70.53
	2041-2070 (2085s)							
Emission Scenario	RCP8.5							
Supply	S_{BL}		S_{10}		S_{30}		S_{50}	
Operational Rule	Present	Modified	Present	Modified	Present	Modified	Present	Modified
Reliability%	99.24	99.70	98.54	99.53	92.25	99.47	83.65	99.11
Resilience%	73.49	60.61	64.38	96.15	24.62	55.17	9.99	35.05
Vulnerability %	23.43	59.25	25.21	41.77	34.30	54.62	43.73	25.09
W.Use Efficiency %	41.60	41.60	45.67	45.75	52.71	54.00	57.99	62.33

Table 4.9 Comparison of performance of present and modified rule curve under RCP4.5.

	2011-2040 (2025s)							
Emission Scenario	RCP4.5							
Supply	S_{BL}		S_{10}		S_{30}		S_{50}	
Operational Rule	Present	Modified	Present	Modified	Present	Modified	Present	Modified
Reliability%	99.74	99.74	97.65	99.24	87.92	99.06	80.78	93.01
Resilience%	68.97	68.97	56.20	37.35	15.86	32.04	5.37	11.10
Vulnerability %	52.61	52.61	30.10	43.91	33.91	32.47	43.29	48.61
W.Use Efficiency %	43.97	43.97	48.08	48.28	54.86	57.05	60.46	63.74
	2041-2070 (2055s)							
Emission Scenario	RCP4.5							
Supply	S_{BL}		S_{10}		S_{30}		S_{50}	
Operational Rule	Present	Modified	Present	Modified	Present	Modified	Present	Modified
Reliability%	98.24	99.16	95.03	99.07	86.67	99.14	80.01	97.24
Resilience%	32.12	33.70	31.56	30.39	11.91	47.87	5.98	33.44
Vulnerability %	35.16	38.06	31.28	44.19	35.66	61.67	44.32	56.69
W.Use Efficiency %	47.57	47.73	51.81	52.46	59.18	61.88	65.27	70.60
	2041-2070 (2085s)							
Emission Scenario	RCP4.5							
Supply	S_{BL}		S_{10}		S_{30}		S_{50}	
Operational Rule	Present	Modified	Present	Modified	Present	Modified	Present	Modified
Reliability%	95.36	99.53	91.34	99.44	84.54	99.12	80.92	98.71
Resilience%	28.94	54.90	26.03	60.66	11.92	34.38	7.46	63.83
Vulnerability %	29.75	39.96	31.26	54.60	36.97	42.32	43.99	36.78
W.Use Efficiency %	41.90	42.45	45.43	46.63	51.97	55.06	58.20	63.45

It is found that while using existing operational strategy, the performance of the system does not remain same for all water supply scenarios and there is tradeoff among performance indicators. Generally, with increase in baseline water supply, the WUE increases gradually whereas reliability and resilience of the system decreases. The maximum reliability of the system is 99.74% while following baseline water supply plan (S_{BL}) in the period of 2055s under RCP8.5 and 2025s under RCP4.5. On other hand, maximum WUE under RCP8.5 & RCP4.5 was achieved for highest water supply plan S_{50} for the period of 2025s and 2055s, respectively, i.e. 67.2% and 65.27%. Under RCP8.5, the most resilient (73.49%) and lest vulnerable (23.43) conditions are seen for S_{BL} plan in 2085s and under RCP4.5

highest resiliency (68.97%) in the system is found for S_{BL} in 2025s and minimum vulnerability in 2085s for same water supply plan.

If we consider it that, under best reservoir operational strategy, the operator must be able to release planned amount of water while keeping the system highly functional for longer period of time. To achieve this target, operator will have to keep the system highly reliable along with efficient use of water resource. But as mentioned reliability of the sytem decreases with increase in water supplies.

However, modification in the existing rule curve are proposed to achieve highly reliable system with efficient use of water.

From Table 4.8 & Table 4.9It is found that after applying modification in current operational rule curves, the reliability and WUE of the system increased for all water supply plans, climate change scenarios and time windows with compromise on resilience and vulnerability at some extant.

It is worth noting that the overall system performance is increased after applying modification in existing rule curves. Here, it can also be mentioned that only increase in flows is not guarantee to make increases in water supplies and role of operational rule curves is very crucial.

As it is impossible to get all performance parameters in ideal conditions, the water resource manager will have to choose most appropriate water supply plan as per needs and objectives of reservoir operation.

As Simly dam is purposely constructed for domestic water supplies, however, the failure of system for longer period cannot be acceptable. Therefore, to address aforementioned objectives of reservoir operations in conjunction with foreseen increasing demand of water, we suggest S_{30} for 2025s and 2055s and S_{50} for 2085s, under RCP8.5, with adapting modified operational rule curves Figure 4.16. Under RCP4.5, same water supply scenarios for same time windows are suggested with modified operational rule curve presented in Figure 4.16.

A considerable difference between current and modified rules is experienced for time window 2085s and it might be addressed as an effect of change in inflow pattern.

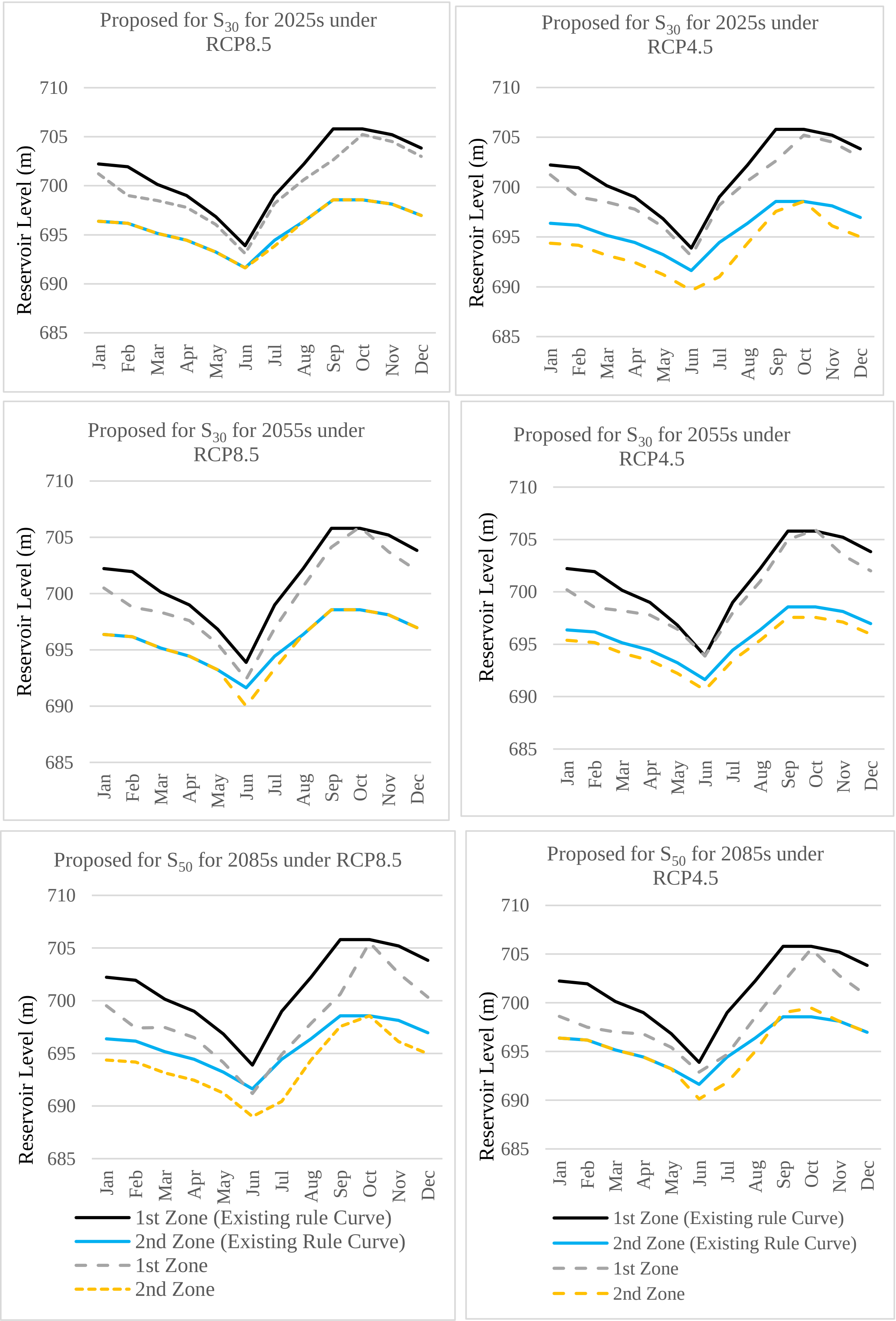


Figure 4.16 Proposed changes in present operational rule curve to enhance reservoir operational performance

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Land use changes in Simly dam catchment may impose long term hydrological impacts. Increase in built up land and decrease in forest cover may aggravate hydrological behavior of the catchment. Increasing built up land and decreasing forest area may lead to decrease in storage capacity by silting up reservoir and increasing hydrograph peaks with decreasing response time and recession limb.

From this study, while using calibrated and validated parameters, HEC-HMS is efficient rainfall-runoff model for Simly dam catchment and can be used for further hydrological impact studies.

It is found that Log-Normal distribution is best fit distribution for catchment to perform frequency analysis. Model simulations for different intensity rainfall events inform that dam structure is safe against overtopping. Climate data used in this study to analyze frequency of precipitation events for Simly catchment, warn that intense precipitation events may occur more frequently from near future 2025s to far future 2085s.

There is prediction of increase in future water availability with inter-annual changing pattern and unequal temporal distribution. There is prediction of increase in future water availability for RCP8.5 by 27%, 26% & 42% for 2025s, 2055s and 2085s, respectively. For RCP4.5 there is prediction of increase in inflow by 27%, 25% and 33% for 2025s, 2055s and 2085s. But an efficient use is possible by counting serious efforts.

2.05 m^3/sec (39 MGD) supply is not rightly explained for Simly reservoir operational rule curves and it should be realistic and representative of demand and availability.

Reservoir operational rules for Simly reservoir will need to modify inevitably, to meet with increasing demand of water in future. Just increase in inflow volume is not surety to provide more water. It could be possible by adapting suggested operational rules defined under climate change scenarios.

This study concludes that projected increase in future water availability, may be used efficiently by taking into count modification of current operational capacities. The future planning, omitting all these aspects may trigger devastating situations.

5.2 RECOMMENDATION

1) Distributed hydrological models (i.e. on the bases of water and energy budget) should be used, to take into count the spatial variability of climate variables.
2) On the bases of reservoir operational strategies discussed in this study, it is recommended to modify current operational strategy.
3) According to 2013 survey, due to sedimentation reservoir have lost its storage capacity by 21.5% from its time of construction. So, by constructing a dam upstream of the Simly reservoir, it may be helpful to increase reservoir life, storage and operational capacity of the system, and to minimize effects of high intensity precipitations. A feasible dam site upstream of the Simly reservoir is available at point of Chaniot (as discussed by CDA authority) and should conduct a study to evaluate impacts of constructing this dam.
4) Current land use changes in the catchment call to apply watershed management techniques immediately.

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