Annual & Seasonal Streamflow Projections to Predict its Trends on Trans-boundary River Chenab under Climatic Scenarios on Control Points of Downstream State

By

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(NUST2017-203431)

A Thesis submitted in partial fulfillment

of the requirements for the degree of

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In

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DEPARTMENT OF WATER RESOURCES ENGINEERING AND MANAGEMENT

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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

NATIONAL UNIVERSITY OF SCIENCE AND TECHNOLOGY

SECTOR H–12, ISLAMABAD, PAKISTAN

This is to certify that the

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Has been accepted in partial fulfillment of the requirements

Towards the award of the degree of

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DEDICATED TO

My Family

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Engr. Ammara Mobeen of (NICE-SCEE) shared observed discharges of control points with referred data for research from Punjab Irrigation Department (PID) individual stations are converted in day-discharge series in excel for projection of precipitation datasets.

My parents supported me on moral and spiritual ground to outcome these goal to maximum efficiency for my homeland. Continuous struggle makes me weak for few months which suspend from my current institute over-come with medical certificate. Special thanks to my mother for time management through-out my research phase.

(Muhammad Rehan Riaz)

ABSTRACT

Streamflow prediction with pseudo-distributed approach in lumped format, according to multi-criteria parameter estimation generate future climatic flows at control points to make the mitigation and adaptation strategies under IPCC scenarios. Chenab River shared basin between India (upper-riparian) and Pakistan (lower-riparian), according to IWT (1960). Biased implementation of civil works lead to data sharing problem due to which lower riparian state faced huge losses under changing climate & mal-operations. This study evolves around future climatic trends of control points in Pakistan with accuracy projections in HEC-HMS. Rainfall datasets of TRMM (satellite) & APHRODITE (interpolated) are compared on daily basis to optimize HEC-HMS in a format of lumped case for each control point to rainfall-streamflow analysis using GIS based SCS-loss method and SCS-Unit Hydrograph transform method with multi-criteria parameter estimation. Calibration is performed on both datasets from 2005-2009 and validation from 2010-2013. TRMM being more efficient to project streamflow at Marala Headworks, Khanki Headworks & Qadirabad Barrage in validation stage due to Influence of upstream state control points on annual basis and TRMM and APHRODITE indicate strong relationship in Kharif season. Annual projection relates 3 efficiency constant of R^2, NSE and P-BISE, At Marala Headworks (R^2, NSE, PBIAS) as TRMM_V & APHRO_V results (0.74, 0.81, -6) & (0.62, 0.57, -13), Khanki Headworks validation results (0.81, -87) & (0.68, -62). Qadirabad Barrage validation results (R^2, PBIAS) as (0.74, -67) & (0.64, -44) respectively. Two seasons of Rabi and Kharif are (TRMM_V, APHRO_V) as (0.11, 0.05) & (-3, -52), (0.14, 0.01) & (-65, -142) and (0.16, 0.12) & (-13, -66) in Rabi season, (0.71, 0.78) & (-30, 9), (0.8, 0.78) & (-95, -36) and (0.58, 0.71) & (-92, -33) in Kharif season respectively. MIROC-5 predict change of (-265, -39, 13), (231, 806, 529) and (64, 611, 520) cumec on three control point of downstream state (Annual, Rabi, Kharif). Prediction with MIROC-5 climate model at Marala Headworks estimate required additional streamflow from Jhelum River of 2.94 cumec while Khanki Headworks and Qadirabad Barrage increase in streamflow from equitant design values.

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AMSL (Above Mean Sea Level)

ASR (Aquifer Storage & Recovery)

ASTER (Advanced Space-borne Thermal Emission and Reflection Radiometer)

ALOS (Advance Land Observing Satellite)

APHRODITE (Asian Precipitation –Highly Resolved Observational Data Integration Towards Evaluation)

AMC (Antecedent Moisture Condition)

CMIP5 (Coupled Model Inter-comparison Project 5)

CORDEX (Coordinated Regional Climate Downscaling Experiment)

CN (Curve Number)

DBMS (Data Base Management System)

DEM (Digital Elevation Model)

DSM (Digital Surface Model)

FAC (Flow Accumulation)

FAO (Food & Agriculture Organization)

FDC (Flow Duration Curve)

FDR (Flow Direction Raster)

GCM (General Circulation Model)

GHG (Green House Gases)

GIS (Geographical Information System)

HEC (Hydrologic Engineering Center)

HMS (Hydrologic Modeling System)

HPP (Hydro Power Project)

HSG (Hydrologic Soil Group)

HWSD (Harmonized World Soil Database)

IDW (Inverse Distance Weighting)

IIASA (International Institute for Applied System Analysis)

IPCC (International Panel on Climate Change)

IWT (Indus Water Treaty)

JAXA (Japan Aerospace & Exploration Agency)

LFP (Longest Flow Path)

P-BIAS (Percent BIAS)

PPM (Parts Per Million)

RCM (Regional Circulation Model)

RCP (Representative Concentration Pathways)

MCM (Million Cubic Meter)

METI (Ministry of Economy, Trade and Industry)

MIROC (Model for Interdisciplinary Research on Climate)

MM (Milli Meters)

MMLC (Mangla Marala Link Canal)

MW (Mega Watt)

NASA (National Aeronautics and Space Administration)

NDWI (Normarlized Difference Water Index)

NSE (Nash Sutcliffe Estimator)

PALSAR (Phased Array type L-band Synthetic Aperture Radar)

RTC (Radiometric Terrain Corrected)

SCS (Soil Conservation Service)

SQ.KM (Square Kilometer)

TRMM (Tropical Rainfall Measuring Mission)

UJL (Upper Jhelum Link)

VBA (Visual Basic for Application)

Chapter 1
Introduction

General:

Chenab river shares basin between India & Pakistan, India as upper riparian state has specific control on water flow according to Indus Water Treaty 1960, three rivers named Indus, Jhelum and Chenab was given to Pakistan while Ravi, Satluj and Beas shared to India. This research focuses on water regulation of Chenab between India and Pakistan according to rainfall-runoff discharge evaluation. Hydro-meteorological datasets will utilize as one was measured through gauges of two countries and then interpolated on scale of 25km similarly second dataset is satellite based remote sensing of same scale. Continuous daily rainfall data from 2005 to 2013 project on lumped format with pseudo-distributed approach to generate streamflow with control points in concerned region. Chenab River covers basin of almost 47k SQ.KM of 11 control points including runoff-river dam, detention storages, and headworks and barrages. Pakistan based controls are headworks and barrages due to mild slope while high slope region includes Indian occupied Jammu & Kashmir. First control point where Chenab River enters into Pakistan is Marala Headworks, from where upstream there is runoff the river dam of Salal was first control point established in upstream state. Khanki Headworks takes input from Mangla Dam while Qadirabad Barrage is supported from Rasul Barrage of Jhelum River. Downstream state has no storage capacity on four control points including Trimmu Barrage, while upstream state capacity in volume storages are available in literature. Main work for this research is to simulate streamflow in HEC-HMS with development of control points to estimate accuracy of Hydro-meteorological datasets on annual and seasonal basis, then parameter sensitivity analysis to set model for prediction with MIROC-5 climate dataset of this century. HEC-HMS with pseudo-distributed approach in lumped format in transboundary with GIS project scarce gauge basin of Chenab to predict future climate change in hydrology. HEC-HMS estimate streamflow with two mode, mode-1 ignore detentions of upstream state while mode-2 consider volume storage in lumped format for accuracy. Transboundary hydrological parameter datasets are not in reach to run HEC-HMS in mode-2, only Dam is control point upstream of

Salal Dam with design parameters available to project hydro-meteorological datasets for calibration, proposed detention control points are still in consideration, so mode-1 is more favorable task to perform in current stage.

Problem Statement:

Indus water treaty was signed in 1960 which assign upper tropical three rivers to Pakistan while upper riparian state of Indian Jammu & Kashmir has full control on lower three rivers. Upper Rivers Include Indus, Jhelum and Chenab while lower Rivers were Ravi, Satluj and Bias. India has specified control of Chenab with general storage of 616.7 MCM and power storage of 740 MCM while it has no flood storage capacity.

Transboundary Rivers generate misleading data sharing problem which cop up with floods and droughts in regions due to unilateral behavior of both countries and climate change on international level. River Chenab was mismanaged after Built-up of Baglihaar dam upstream of Salal dam which has very low storage capacity left. Main issue of Pakistan is high spillway crest

River System	General Storage **(MCM)**	Power Storage **(MCM)**	Flood Storage **(MCM)**
The Indus	308.4	185	Nil
The Jhelum (Excluding Main)	616.7	308.4	925
The Jhelum (Main)	Nil	Nil	Para 9 (IWT)
The Chenab (Excluding Main)	616.7	740	Nil
The Chenab (Main)	Nil	740	Nil

of 4.3m which increases its storage in Rabi season. Climate change is another issue in this region Pakistan is on 7th number in list with most Influence countries of the world.

Objectives of the study:

Three main objectives were on agenda for this research first one id check of rainfall data which is interpolated from current states observed of APHRODITE and satellite based data of TRMM for simulation of rainfall-runoff model, second is to project hydrological Influence with hydrograph in Chenab region for current and proposed control points in lumped format which are sub-basin. Last one is to predict seasonal and annual climate change assessment for MIROC-5 RCPs with long term century fluctuations of streamflow.

Research Hypothesis:

Hypothesis includes Chenab detention point's area with respect to its volume calculations in hydrograph format and time evaluation of almost 9 years on daily basis. Research combines work of the multiple projects with irrigation water available on seasonal and annual scale in Pakistan and Indian occupied Kashmir.

Scope of the Study:

Chenab Basin covers total area of 46357 (SQ.KM) in both transboundary catchment with 11 control points 4 in downstream region of Pakistan while 7 includes detentions in upstream with steeper slope. Basin perimeter is almost 2563 Km.

Constructed Controls:

Indian:

First control point was established in Chenab Basin is Salal HPP which start operating in 1989 with power generation of 690MW at an elevation of 489 (AMSL) which is currently consider as a run-off-river dam.

Next control point Dul-Hasti of this basin's time span was established in 2007 with power generation of 780MW at an elevation of 1267 (AMSL) and live storage capacity of 12.98 MCM and total live storage capacity available for India on Chenab is 740.1 MCM.

Third main control point on Chenab is Baglihaar HPP which power generation capacity of 900MW at an elevation of 840 (AMSL) which is most discussed and focus point of this study with live storage of 496 MCM.

Pakistani:

Major control points in downstream with milder slope of lower riparian region are four out which three were streams through Chenab basin while one include both Chenab and Jhelum basin.

First control point Head-Khanki which was established in 1892 with design discharge of 22653 cumec for irrigation currently under control of PID. Second established was Qadirabad Barrage with design discharge of 25485 cumec in 1967. Third is entrance Point of Chenab River in Pakistan Head-Marala with design discharge of 31000 cumec established in 1968, Trimmu Barrage downstream of Chenab and Jhelum rivers confluence is not under scope of this study mainly comprises Chenab basin. Confluence point is 32.56 (KM) above barrage.

Under-Construction Controls:

Upper-riparian state of India in Jammu & Kashmir proposed and building dams for irrigation and power generation using Chenab water according to IWT 1960 with maximum live storage capacity of 740.1 MCM.

Pakal-Dul HPP is currently under construction with live storage of 167.5 MCM and power generation of 1000 MW out of which 59.1 MCM will be diverting towards Dul-Hasti through tunnel construction. Ratle dam is also under construction with live storage of 10 MCM and power generation of 850 MW.

Proposed future dams are Bursar and Sawalkot, At most steep slope of Glacier region Bursar HPP will be constructed with power generation of 800MW and live storage is 1294 MCM. Sawalkot is downstream of Baglihaar HPP with live storage of 2013 MCM and power generation capacity of 1200 MW.

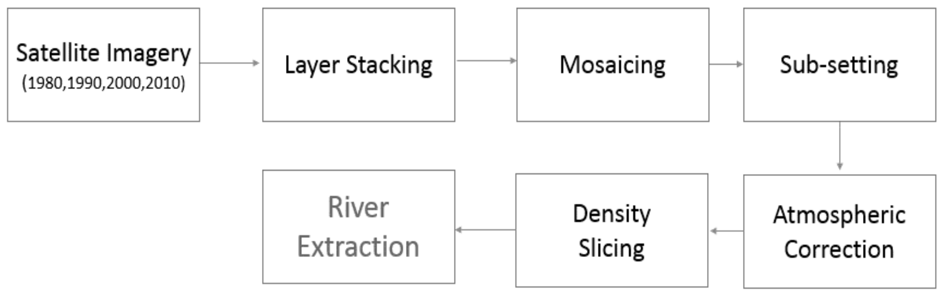
Organization of thesis:

Chapter 1 contains introduction about write-up; general description and problem statement with objectives to be implemented and research hypothesis, Scope of study covers total area. Chapter 2 contains literature review which include papers to be reviewed and its data description with comparison. Chapter 3 has thesis methodology flow chat and its main contents first preprocessing of primary datasets of DEM, LANDSAT and FAO. TRMM & APHRODITE datasets extraction on area-average time series then HEC-HMS model converted in lumped format and Climate Change assessment methodology on basis of MIROC-5. Chapter 4 describes about results and discussions with developed HEC-HMS outputs on seasonal and annual scale of three controls in Pakistan on individual level. Chapter 5 gives conclusions and recommendations about research thesis and lastly the bibliography.

Chapter 2
Literature Review

General:

Transboundary river Chenab basin covers four control station one which most downstream structure is Trimmu-barrage constructed after confluence of Chenab with Jhelum. Study on Chenab Basin has to cover last point, so no model developed before for this region on high spatial resolution datasets. One research entitled *"Transboundary Impact assessment of Indian dams: A case study of Chenab River Basin in perspective of Indus Water Treaty (2015)"*



Done for sole Chenab catchment with no model incorporation, covers generally management framework, water quality, quantity and impact assessment of stoppages while construction of Baglihaar Dam.

Second research work entitled" *Geospatial Analysis of planned Indian dams on river Chenab and its hydrological and agriculture impacts on Pakistan (2017)"* similarly no hydrological and climate study performed for whole catchment of Chenab basin in model.

Only statistical analysis of observed discharges on seasonal basis with crop water deficiency calculations and GIS based NDWI Area extraction of already built and future structures were incorporated.

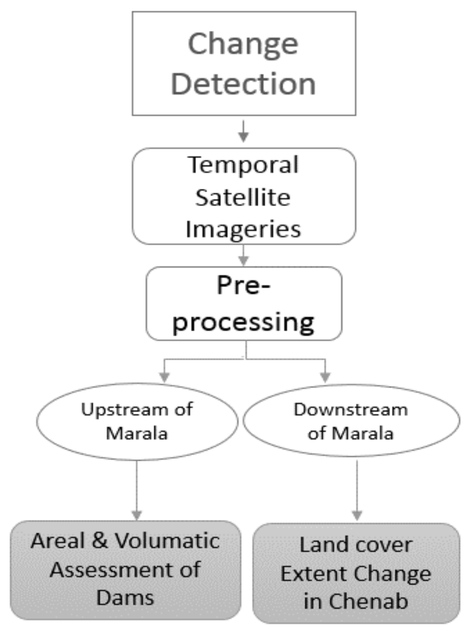


Figure 1: Change Detection

ArcGIS 10.X Processing:

Commercial based ArcGIS 10.X versions with catalog for data handling and map for processing geographical information for desktop are used to generate and analysis of query in digital format. Analyst used python based models to evaluate parameters on spatial and temporal resolution while data sharing availability through servers are through web portals.

Spatial Analysis of Detentions:

Satellite based datasets in ArcGIS map is spatially and temporally done on professional desktop with multiple analysis method of NDWI (Normalized Difference Water Index) and raster band pixels calculation DR (Detected Reservoir) helps predict detention area and volume to compare it with literature.

Change Method:

Reference Reservoir –RR (NDWI)

$$NDWI = \frac{Band\ Red - Band\ SWIR}{Band\ Red + Band\ SWIR}$$

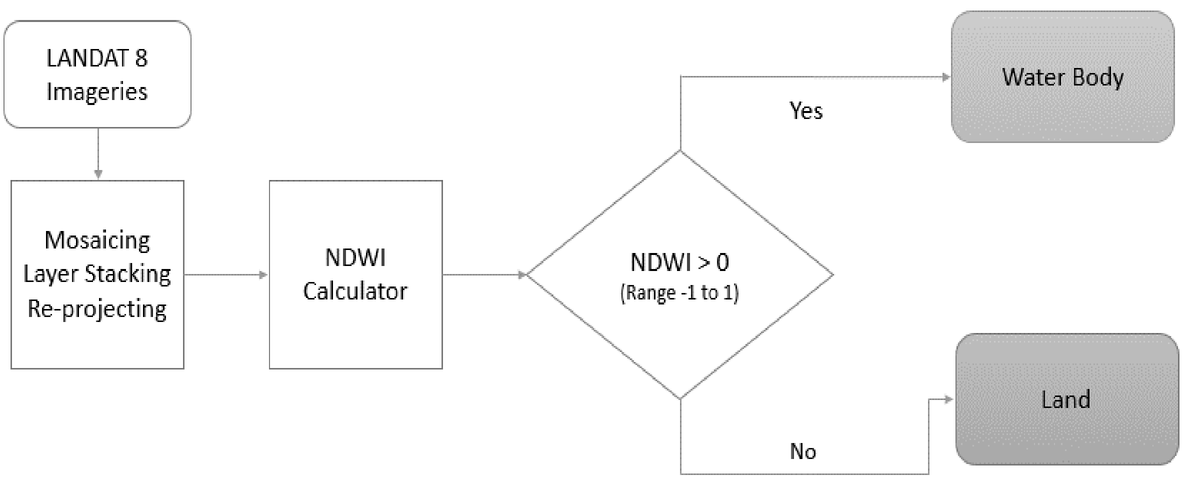


Figure 2: Reference Reservoir

Detected Reservoir –DR (DEM)

Reservoir Elevations using 30m Digital Elevation Model were extracted by using Extract by Mask, Polygon area covers Reservoir Area and Z-value gives vertical distance.

Accuracy Assessment:

Assessment of accuracy of above two analysis products are done by three procedures.

Area Parameters	Description	**Baglihaar** (Sq. meter)	**Salal** (Sq. meter)	**Dul Hasti** (Sq. meter)
False Positive (FP)	Detected area without RR	1,071,480	2,249,780	259,005
True Positive (TP)	Area containing both RR & DR	6,566,839	4,592,920	484,050
False Negative (FN)	Undetected area	1,564,962	992,705	176,550

Table 1: Control Point- Area Parameters

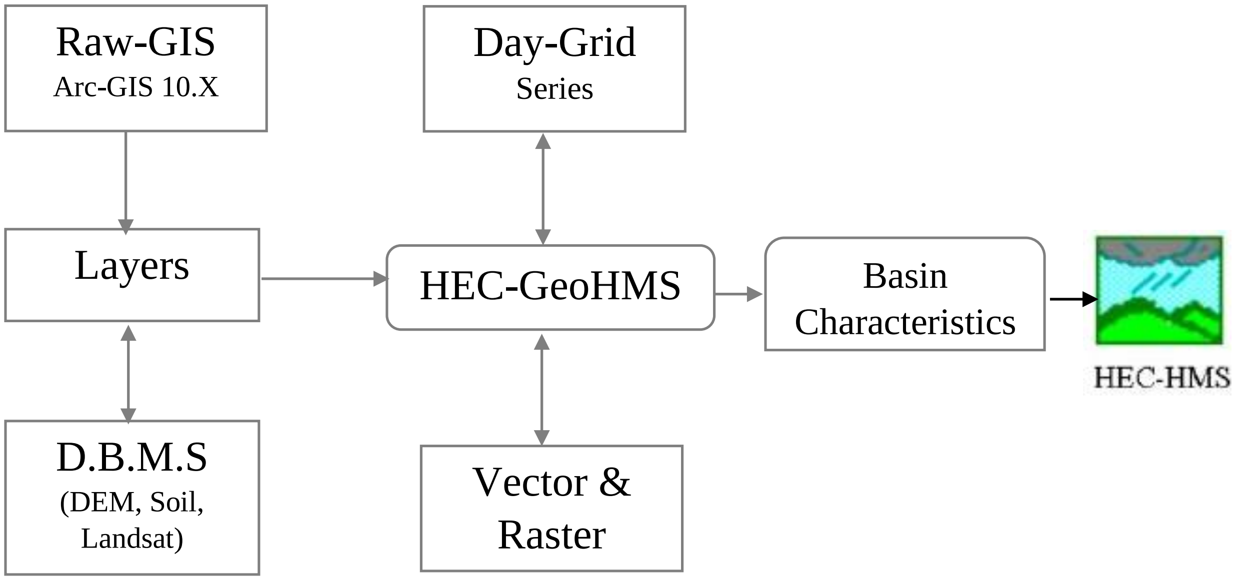
Area Accuracy	**Assessment**	**Baglihaar**	**Salal**	**Dul Hasti**
Branching Factor	FP/TP	0.16	0.48	0.53
Miss Factor	FN/TP	0.24	0.21	0.36
Detection %	100 x [(TP)/(TP+FN)]	80.8	82.22	73.27
Quality %	100 x [(TP)/(TP+FP+FN)]	84.3	58.6	52.63

Volume Accuracy	**Baglihaar** (MCM)		**Salal** (MCM)		**Dul Hasti** (MCM)	
Surface Volume (ArcGIS)	496	Over Estimation of 4.4 %	N/A	Cannot be performed with DEM Imagery	11.83	Under Estimation of 8.85 %
Actual in Literature	475		N/A		12.98	

Table 2: Control Points- Area & Volume Accuracy

Overview of HEC HMS:

HEC (Hydrologic Engineering Center) under US Army Corps of Engineers developed HMS (Hydrological Modeling System) for simulation of continuous and event based processes of whole watershed in sub-basin format which predicts stream flows in specified catchments developed using GIS database.



HEC-GeoHMS Tools:

Terrain and climate data handling extension added in commercial software for DBMS (Database Management System). Python development in ArcGIS based tools are available for processing of raw geographical database for export purpose towards hydrological assessment of watershed delineation. Rainfall-Runoff analysis on basin level generates hydrograph for peak and leap inflow and outflow estimation.

Rainfall-Runoff Analysis:

Prediction of runoff using standard lumped, semi-distributed and fully distributed models with precipitation in solid and liquid formation with terrain parameter estimation simulate for comparison of observed runoffs. Simple mean rainfalls in accumulation removes thresholds of snow-cover area in lumped models while fully distributed models regulates with it in grids. Precipitation products are available for free of cost at high spatial resolution of minimum 0.25 degree approximately covers latitude and longitude area of 25 SQ.KM. Interpolated datasets are gauge observed data of specified country on above mentioned spatial resolution while satellite datasets predict precipitation through cloud formation and then convert it into color theory algorithms. Runoffs are of three types at top surface discharges are measured after removal of sub-surface discharges and last is ground water table know as base-flow which eventually drains in to surface discharges after long time spans.

Models of complex category are developed with equations of all these considerations. HEC-HMS is lumped model used for two main runoff routing methods in single basin through kinematic wave equation and Muskingum 'K' and 'x' value.

Terrain information through HEC-GeoHMS inputs slopes, longest flow paths, lag time, loss coefficient and basin area for tuning a single watershed to estimate unit-hydrograph. These hydrographs for different time duration shows peak and lean runoff with in that watershed.

HEC-HMS predicts rainfall-runoff analysis quite accurately for scarce-gauge precipitation fed region of Jhelum basin in winter while comparing it with SRM which takes precipitation as a liquid and solid form to accurately simulate runoff in summer season of snow-melt duration (*Azmat et al., 2015*).

Terms used for Climate Studies:

Two terms used in hydrology for precipitation and temperature evaluation first is weather and second is climate. Weather represent short term indication of these parameter while climate is long term change. Researcher usually deals with climate change assessment for hydrology through GCM (General Circulation Models) and down-scale level RCM (Regional Circulation Models).

TRMM & APHRODITE Comparison:

TRMM is satellite based data of combine mission between two working groups includes NASA (National Aeronautics and Space Administration) and JAXA (Japan Aerospace Exploration Agency), Tropical Rainfall- Measuring Mission develops for precipitation accounting of tropical regions of the earth with low inclination tilt of 35 degree from equator (Reference fields) and field measuring slope at an altitude of 403 km. TRMM satellite rotates with time span of 90 mins for complete earth rotation and 16 rounds per day.

APHRODITE is interpolated RCM (Regional Climate Model) data of dense measured rain gauge stations with domain of Monsoon Asia, Russia Japan and Middle East with varying spatial resolution. Long term APHRODITE (Asian Precipitation –Highly Resolved Observational Data Integration Towards Evaluation) is grid-based precipitation and temperature product available on daily scale.

(*Levina et al. 2016*) compare TRMM and APHRODITE datasets for droughts analysis, TRMM gives better results for SPI (Meteorological Drought Index) of 3-12 months while APHRODITE on the other hand only index it for 1 month. Similarly TRMM generates better correlation of SRI (Hydrological Drought Index) than APHRODITE.

GCM Comparison:

GCM (General Circulation Models) are understanding of climate and weather on different time scales used physical law to simulate energy distribution with in the globe with mathematical equation on basis of past, present and future datasets regarding precipitation, temperature and surface moisture. Oceans, cryosphere, land and atmosphere incorporated to develop these results of quantification and identification of earth systems with variable estimation which are due to anthropogenic activities. General circulation models (GCMs) are mathematical models capable of representing physical processes of the atmosphere and ocean to simulate response of global climate to the increasing greenhouse gas emission (*IPCC, 2013*).

MIROC (Model for Interdisciplinary Research on Climate) developed latest dataset of MIROC-5 for atmosphere-ocean with comparison of previous version MIROC 3.2 (*Watanabe et al.2010*). Better results of mean fields with respect to previous state variables are generated with observations. MIROC-5 resolution shows lesser difference while comparing with previous 2 versions indicating greater enhancement in parameter schemes making it more sensitive.

36 CMIP5 (Coupled Model Inter-comparison Project 5) metrics generated on temporal differences while little focus of spatial resolution in Pakistan to check mean, annual, pre-monsoon, monsoon, post-monsoon and winter precipitation and maximum and minimum temperature variables. Merge through simple means and regression coefficient indicates ranking of NorESM1-M, MIROC-5, BCC-CSM1-1 and ACCESS1-3 as best GCMs for time period of 1961-2005 through efficiency measurement with observed variables. (*K. Ahmed et al.2019*)

RCP Comparison:

RCP (Representative Concentration Pathways) were defined by IPCC (International Panel on Climate Change) on the base of anthropogenic GHG (Green House Gases) emissions main factor enforcing by population growth, energy utilization, land-use pattern shifting, and economic activities. Four mitigation scenarios developed to evaluate atmospheric concentration of these emissions RCP 2.6 as stringent scenario, two immediate scenarios of RCP 4.5 and RCP 6.0, one high GHG emission scenario of RCP 8.5.

GHG in atmosphere rises surface temperature to specific degree in future with-in these scenarios relative to past anthropogenic emissions. High confidence of surface temperature likely to exceed of 1.5 °C for RCP 4.5, RCP 6.0 and RCP 8.5 in end of current century from (2081-2100) relative to (1850-1900).

Likely Rise °C	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
(2081-2100) *Relative* (1986-2005)	0.3 – 1.7 degree	1.1 – 2.6 degree	1.4 – 3.1 degree	2.6 – 4.8 degree

Table 3: RCPs Temperature Increment

Precipitation changes over spatial resolution will not be uniform. Mid-Latitude and subtropical dry regions experience likely decrease in mean precipitation while many mid-latitude wet subtropical regions shows likely increase in precipitation under RCP 8.5 scenario.

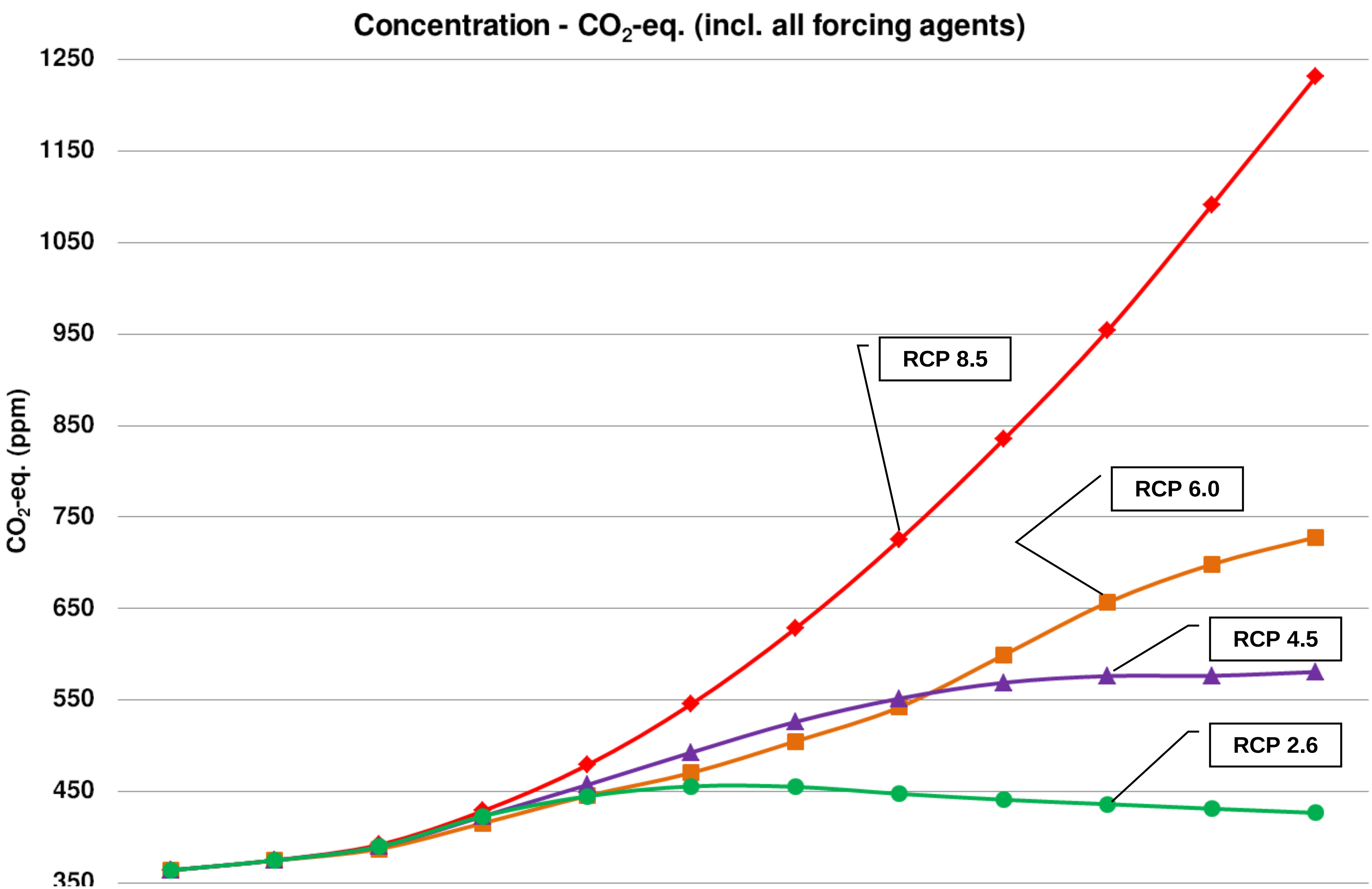


Figure 3: RCP Pathways

Chapter 3
Methodology

Flow Chart:

Terrain

Geographical representation of earth surface entities in three dimensional space of x, y and z values to compute physical phenomena after pre-processing and possessing stages. ‘3D’ datasets in digit format of ‘1’ and ‘0’ are primary source available at free of cost. Geoid for different earth representations are base to reference these values. Imaginary lines of latitude and longitude are drawn in degree, minute and seconds on actual global from equator at zero latitude with positive and negative up and down respectively. One degree latitude change shows distance of almost 111.2 km in vertical direction while one degree longitude is equal to 111 km in horizontal direction. Raster values are grid representation while vectors are point, line and polygons.

Climate

Temporal hydro-meteorological datasets are either observed point interpolated through kriging method or satellite project on these vertical and horizontal spaces. Gauge data receive accumulated meteorological values from droplet in ‘mm’. Prediction of hydrological phenomena in scarce-gauge basin is usually done with these two mechanisms. Models are meteorological dataset which project future climate based hydro-conditions.

Sub-basin

Watershed delineation through satellite observed values represented in basin as a whole catchment and further division into multiple small catchments (Sub-basin). Outlet point situated on streamline within that single basin. Contours separate ridges from valleys on the basis of slope single catchment or basin has single outlet point where discharges are observed from multiple sub-basin’s outlet points.

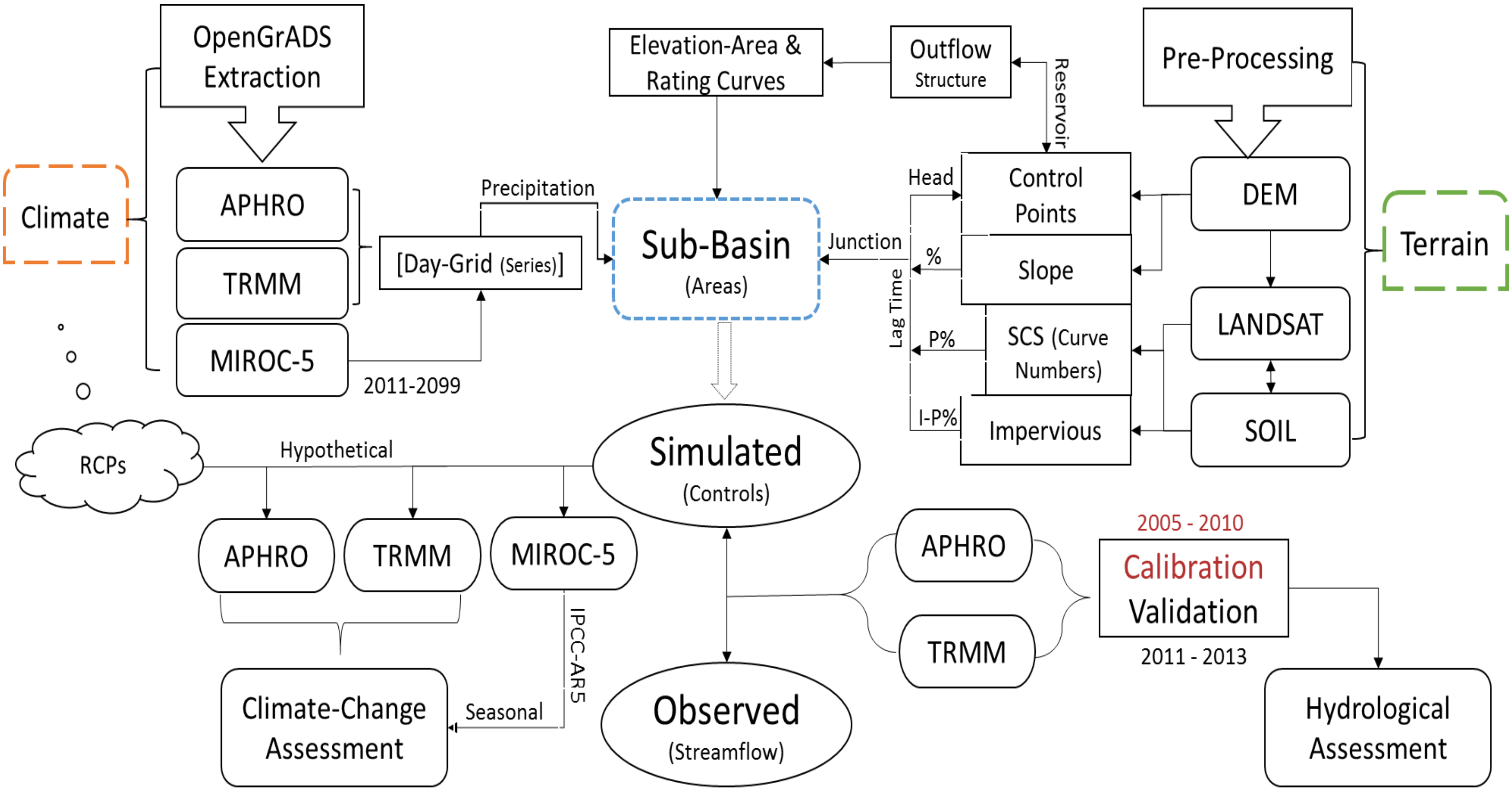


Figure 4: Methodology

Pre-Processing:

Pre-Processing on raw dataset are managed within DBMS (Data Base Management System) of importing the required input layers, symbolical representation of pointers in reality. Queries on layers read parameter of subsets through which missing values are estimated within required region. Categories of individual shapefile has been integrated to extract non-spatial attributes with standardization ID procedure and then splitting values to reduce required inputs.

Study Area:

Chenab River basin originates from Lahaul & Spiti district of Upper Himalayas region include himachal state India and flows through Jammu & Kashmir into plain areas of Punjab Pakistan at discharge point of Uch Sharif. Two rivers confluence to form Chenab at upstream of Chandra & Bhaga approximately 115 km and 60 km before Tandi.

Chenab Basin covers latitude of 31.7 to 34.3 (289 km) and longitude of 71.9 to 77.8 (655 km) total area enclosed is 46357 SQ.KM. Transboundary Chenab basin is fertile in aspect of agriculture production with prone to flood as well, upstream elevation changes from 7055m to 750m, At Marala Headworks downstream elevation where river enters into Pakistan elevation change is only 631m up to confluence with Jhelum River. Total Chenab basin area at upstream of Indian state is 26316 SQ.KM approximately covers 57% and downstream area of 43% in Pakistan state is 20041 SQ.KM. Monsoon-Asia region of Chenab receive less rainfall in winter while JJAS (June, July, August, September) has maximum values. Two dominating seasons of Rabi (winter) and Kharif (summer) are policy making factors for hydrological assessment in Chenab requires precipitation and economic growth statistics.

TRMM and APHRODITE rainfall data from 2005-2013 on daily basis comprises on annual and seasonal difference results mean annual 2.71mm & 2.26mm, and maximum annual values of 56.51mm & 39.29mm respectively on 25 x 25 km grid, Mean seasonal TRMM and APHRODITE rainfall in Rabi season is 1.38mm & 1.77mm shows decrement of 49% & 22% while in Kharif season 4.07mm & 2.77mm increment of 50% & 22% respectively from annual.

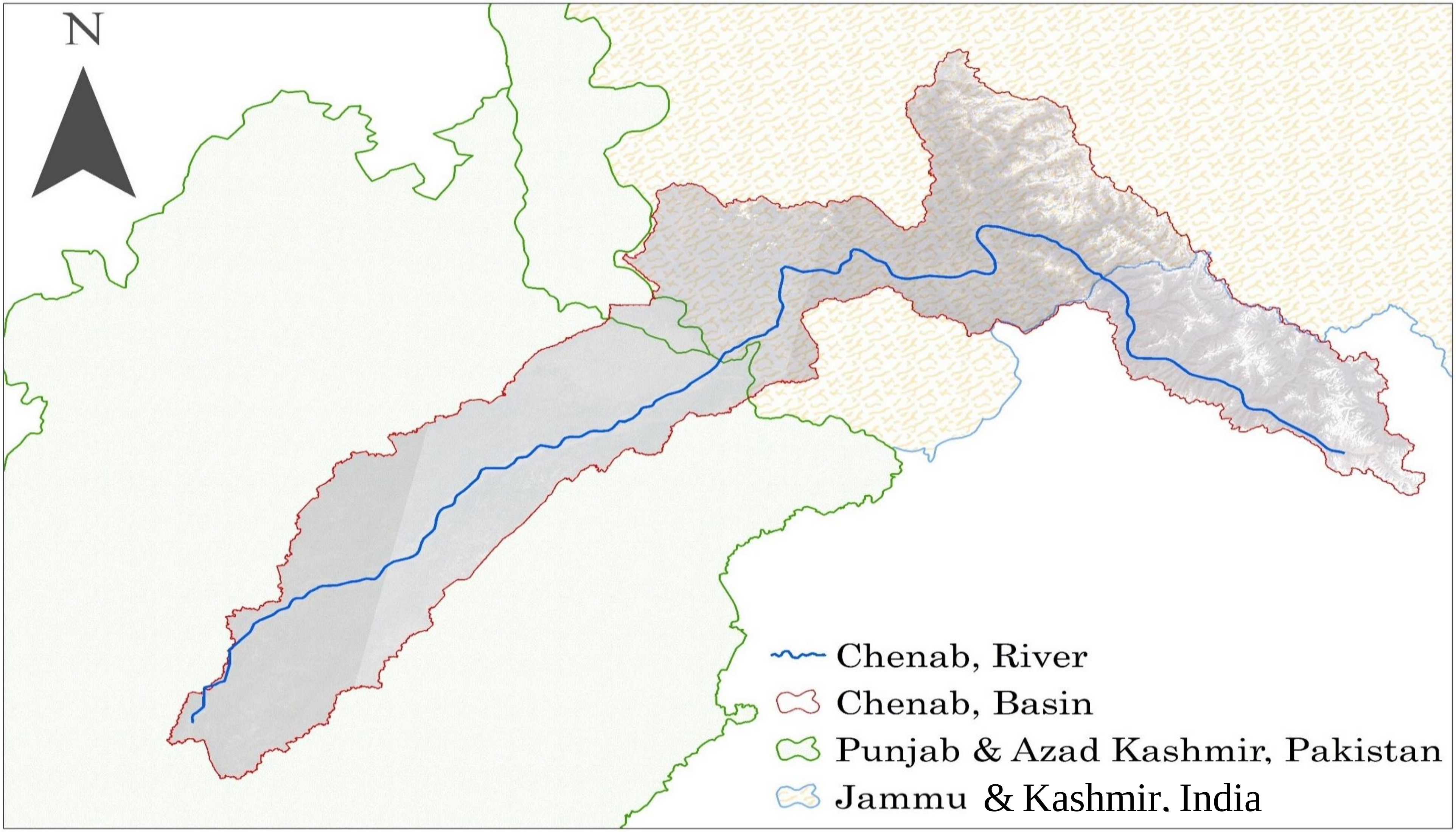


Figure 5: Chenab Study Area

DEM Dataset:

Geographical representation of terrain in 3-Dimentional space 'X' & 'Y' horizontal with Z-score as third axis is interpolated information from known datum point- vector data elevation extension after ground surveys and photogrammetric data capture in grid-raster format. DEM (Digital Elevation Models) are bare-land information no trees and buildings having contradiction of man-made feature representation with DSM (Digital Surface Model).

DEM used for parameter estimation of earth geomorphology in hydrology and mass movement to generate streamlines, slope, sediment transport and soil wetness analysis. Spatial resolution varies for these open-source and commercial dataset of different products, high accuracy open-source requirement grid with 12m x 12m covers surface land of this magnitude.

ALOS & ASTER Comparison:

Japanese Earth-observation satellite capture terrain information developed by JAXA (Japan Aerospace Exploration Agency) with name of ALOS (Advance Land Observing Satellite) for terrestrial, topography and geology assessment, climate and hydrological processes, renewable resources and disaster management. ALOS – PALSAR (Phased Array type L-band Synthetic Aperture Radar) RTC (Radiometric Terrain Corrected) datasets of RTC-1 with resolution of 12.5m and RTC-2 of 30m are available for free-of-cost.

United States NASA (National Aeronautics and Space Administration) and Japan METI (Ministry of Economy, Trade, and Industry) jointly lunched terra satellite for ASTER (Advanced Space-borne Thermal Emission and Reflection Radiometer) G-DEM (Global Digital Elevation Model) data interpretation in digital format, Minimum of 30m spatial resolution is available for this product.

Streamlines are output vector files of FDR (Flow Direction Raster) and FAC (Flow Accumulation) dataset two different products of above mentioned satellites are utilize for indication, different spatial resolution shows major error of hydrological assessment from reality. Tawi river is left bank tributary of Chenab river that flows downstream in case of ASTER, while no drainage issue for ALOS where it actual streams into Marala-Headwork. ALOS indicate that Chenab drains into 31km upstream of confluence with Jhelum River. Where no discharge measurement activities are performed for hydrological analysis, more accurate data of ALOS-PALSAR is preferred for current study. Streamline's lengths and slopes attribute for HEC-HMS inputs to simulate streamflow for model calibration and projection of future climate in Chenab basin, Slope of Chenab basin in percent-rise calculation for whole basin and further sub-basins are performed which is measurement of angle from horizontal axis to maximum 45° show maximum value of 100% while change in minimum value with this angle, Lag time is index of location between precipitation peak center point to hydrograph peak value in horizontal direction.

Basin-Division:

Chenab basin is divided into sub-basin in HEC-GeoHMS extension toolbar on FAC raster with control points in streamline to make lumped formation. Polygons of default output merge into single lumped then latitude and longitude from google earth pro version convert in 'x' and 'y' of interest where streamflow projections to be made, 11 control point defines on Chenab river for estimation of model. Control point is junction and reservoir interpretation of drainage area in lumped format, sub-basin area at control point is polygon shapefile geometry evaluation in SQ.KM. Junction is confluence of one or two streams with no storage capacity and addition of discharge into downstream junction while reservoir is outflow structure with rating curve which is Elevation-Discharge relationship for fully merged spillways and Elevation-Area curve.

HEC-HMS runs on two mode with no storage in junction (mode-1) formulation and for reservoir (mode-2) of reverse modeling where storages are calculated from design parameters of structure, only mode-1 considers to calibrate due to scarce gauge Chenab basin and transboundary data sharing problems.

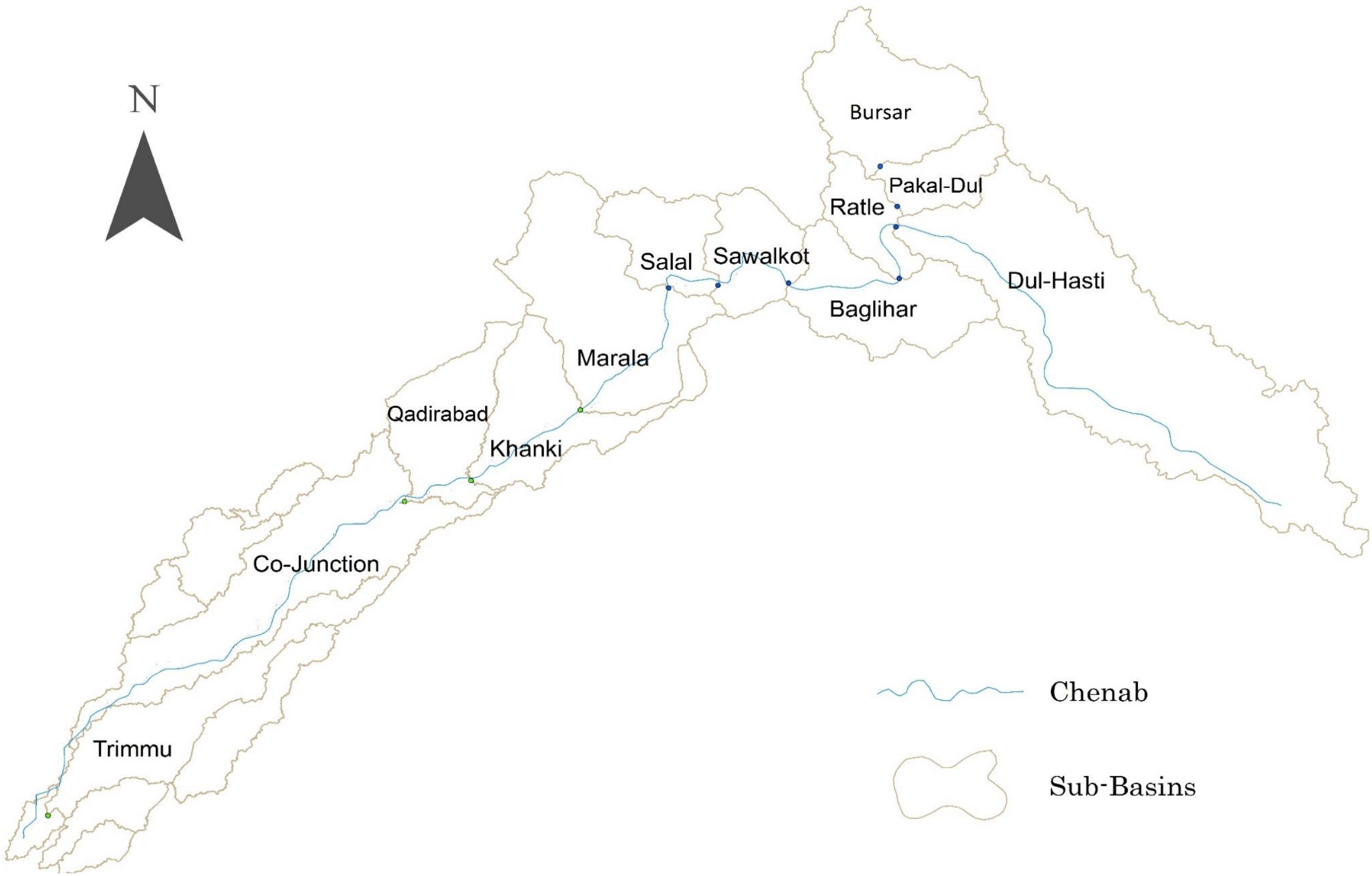


Figure 6: Sub-Basin

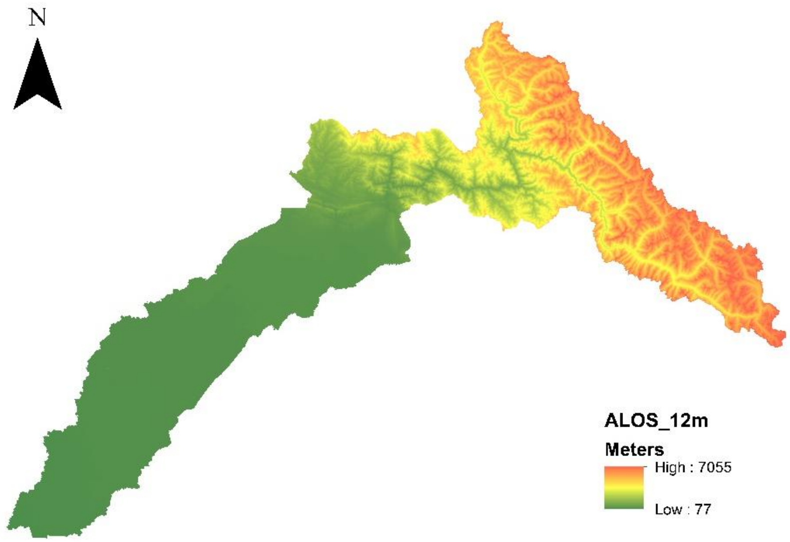


Figure 8: ALOS DEM

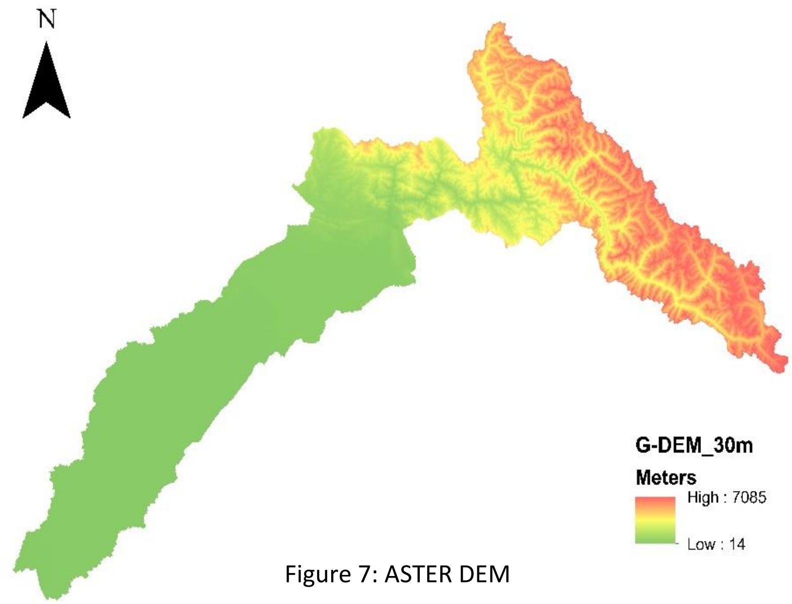


Figure 7: ASTER DEM

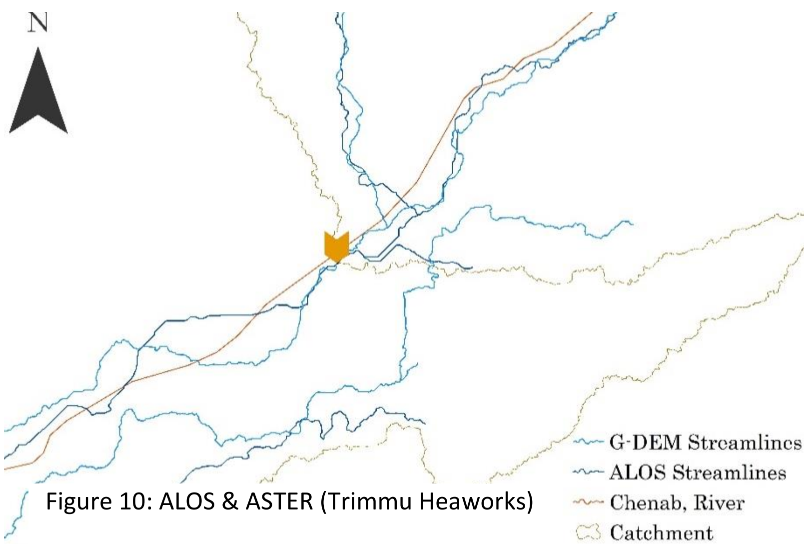


Figure 10: ALOS & ASTER (Trimmu Heaworks)

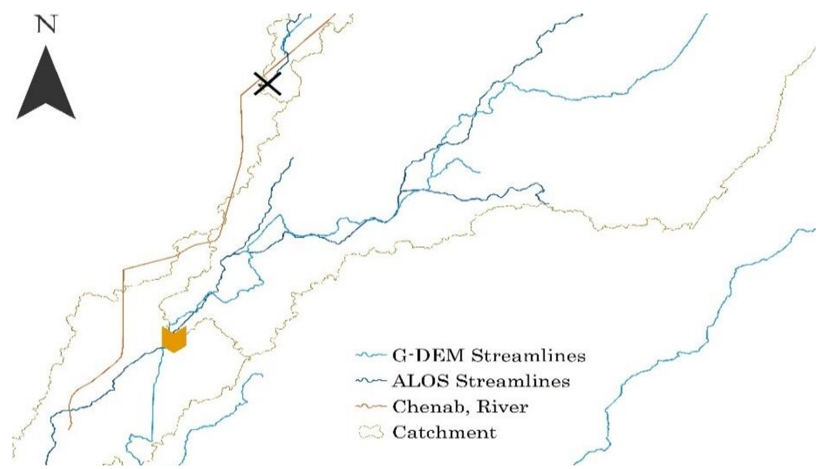


Figure 9: ALOS & ASTER (Marala Headworks)

Landsat Dataset:

Landsat satellite mission has multiple temporal version of 1-9 having scanner and thematic mapper capabilities. Landsat-5 version dataset used with 7 bands and launching duration from 1984 to 2013 carrying Multi-Spectral Scanner (MSS) and thematic mapper longest earth observatory mission in history launched by NASA.

Land-Cover Classification:

Land-Cover data in raster format for spatial indication of land properties on 27m x 27m real earth resolution is secondary source information generated from Landsat-5 temporal resolution of 2011, band combination of 7-4-2 after mosaicking tiles and extracting the Chenab basin, maximum likelihood classification through signature files of Green-lands, Glaciers, Bare-lands and waterbodies with supervised method.

FAO Dataset:

Harmonized World Soil Database (HWSD) is collaboration of Food and Agriculture Organization (FAO), International Institute for Applied System Analysis (IIASA), ISRIC-World Soil Information, Chinese Academy of Science, Institute of Soil Science and Joint Research Centre of the European Commission (JRC).

1km raster data format developed with soil samples and satellite base information of 15000 soil mapping units. Linkage of information on attributes and query through GIS provide characteristic of selected input soil.

Soil-Cover Classification:

Symbolic grid representation defines in polygon attributes of Hydrologic Soil Groups (HSG) for categorization in A, B, C, and D from percent Gravel, Sand, Silt and Clay. Visual Basic for Application (VBA) scripts the field value for individual HSG through ‘if’ and ‘else’ statement in percentages.

```
Dim Output
If  [SU_SYM74] = "A" or [SU_SYM74] = "B" Then
      Output = 100
elseif  [SU_SYM74] = "C"  Then
      Output = 50
end if
```

Figure 11: Soil Percentage Script

Pervious Percent Dataset:

Soil Conservation Service (SCS) Curve Number (CN) is simple accumulative precipitation loss method used in hydrology for surface runoff. DEM, Intersect polygon and Lookup Table generate raster data of CNGrid in HEC-GeoHMS. CN value range (1-100) is indication of runoff with 100 as maximum phenomena on 12m spatial resolution grid estimate junction discharge of specific sub-basin though CNGrid, Antecedent Moisture Condition (AMC), and grid location from junction.

Intersect:

Intersection of two polygon shapefiles of Land-Classification and Soil-Cover Classification intersect the column attribute values ‘PctA’, ‘PctB’, ‘PctC’ and ‘PctD’ of both these dataset with which class of land contains how much pervious percent of HSG, ‘PctD’ has 0% ‘D’ category shows only sand, silt and clay in total 100% and no incorporation of gravels, then one add field of ‘LC-Value’ reads GRID-ID for lookup-table.

Lookup Table:

Four attribute column in reference table of HSG for multiple Land-use standards are available for runoff estimation according to infiltration rates ‘A’ category has high infiltration rate due to sandy soil while ‘D’ category show low infiltration rates of clayey soil. One LC-Value column read data of GRID-CODE from intersect polygon.

Impervious Percent Dataset:

Percentage of three pervious soil strata define Curve Numbers (CN) for loss estimation while impervious soil is gravel part division from pervious soil. 1000m grid of FAO-Soil data provided with gravel percent in tabular format to estimate impervious percent soil strata.

SCS-Unit Hydrograph:

SCS-Unit hydrograph is transformation method of accumulative precipitation into streamflow through reach progress into junction after losses. Unit hydrograph is streamflow indication of unit precipitation phenomena in specific sub-basin with SCS-Lag time (T_P) which takes percent slope (S), mean curve number (CN), longest flow path (L), analysis time step (Δt) in minutes and impervious percent and constant area parameter estimation.

$$T_P = \max\left(\frac{L^{0.8}\left[\left(\frac{1000}{CN}\right) - 9\right]^{0.7}}{31.67\, S^{0.5}}, 3.5\,\Delta t\right)$$

T_P = Sub-Basin Lag Time (min)
L = Sub-Basin Longest Flow Path (m)
CN = Sub-Basin Mean Curve Number
S = Sub-Basin Slope (%)
Δt = L / V (min)
V = C * N
C= 6
N = Sub-Basin Number

Uncertain parameter of lag time shifts with value of constant 'C' in inverse relationship to indicate decrease of 33% and increase of 60% as maximum and minimum. Sub-basin numbers are in descending order from downstream to upstream as Chenab basin division were performed for downstream control point of Trimmu Barrage confluence with Jhelum towards last control of Dul-Hasti due to catchment characteristics.

SCS-Unit Hydrograph attenuation is phenomena for capturing peak runoff through rising limb as lag time decrease curve number increase in inverse relationship so it will attenuate from upstream to downstream state. TRMM & APHRODITE rainfall datasets are stacked in hydrograph format to reanalysis of streamflow for accuracy and favism assessment.

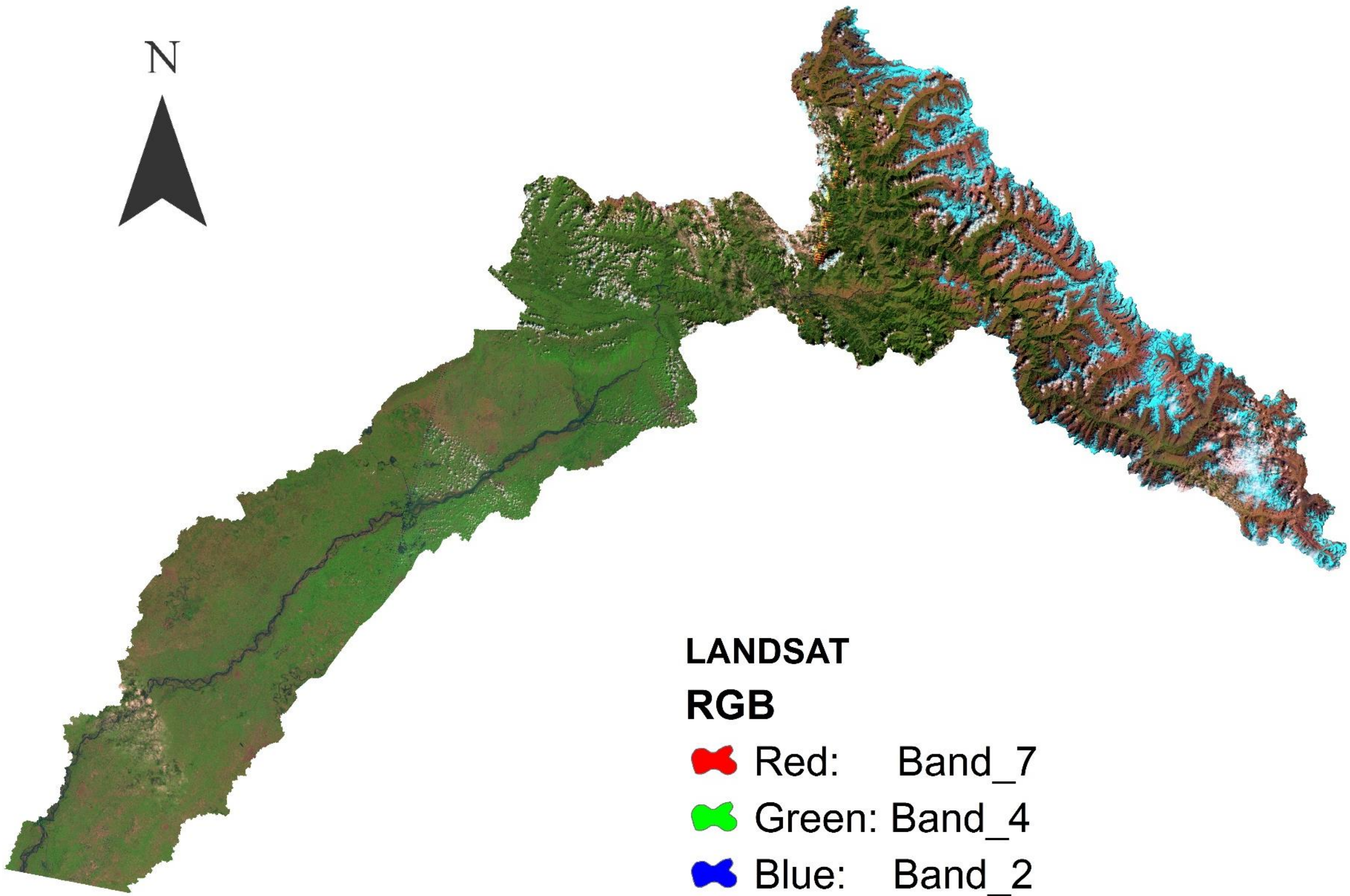


Figure 12: Landsat

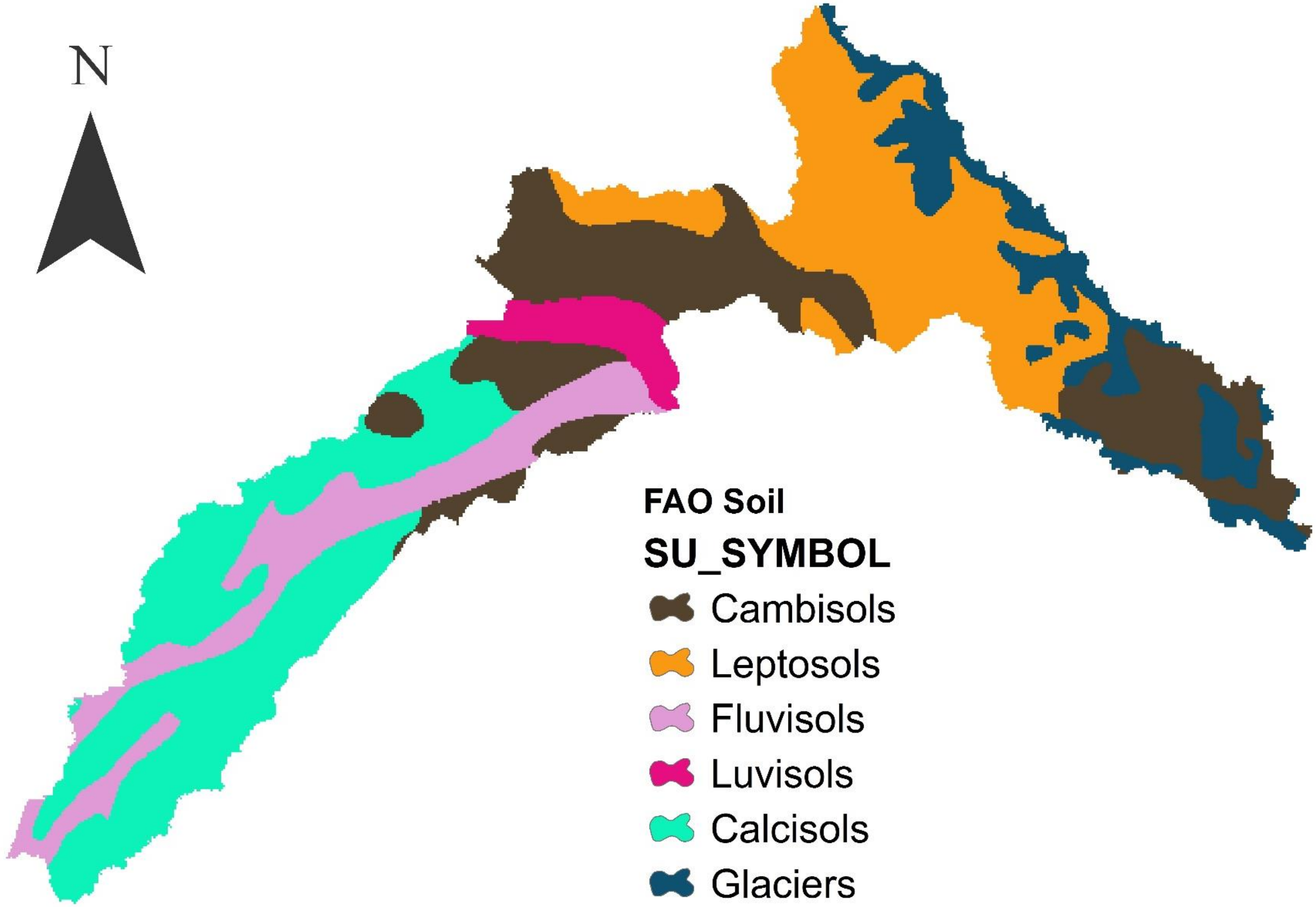


Figure 13: FAO

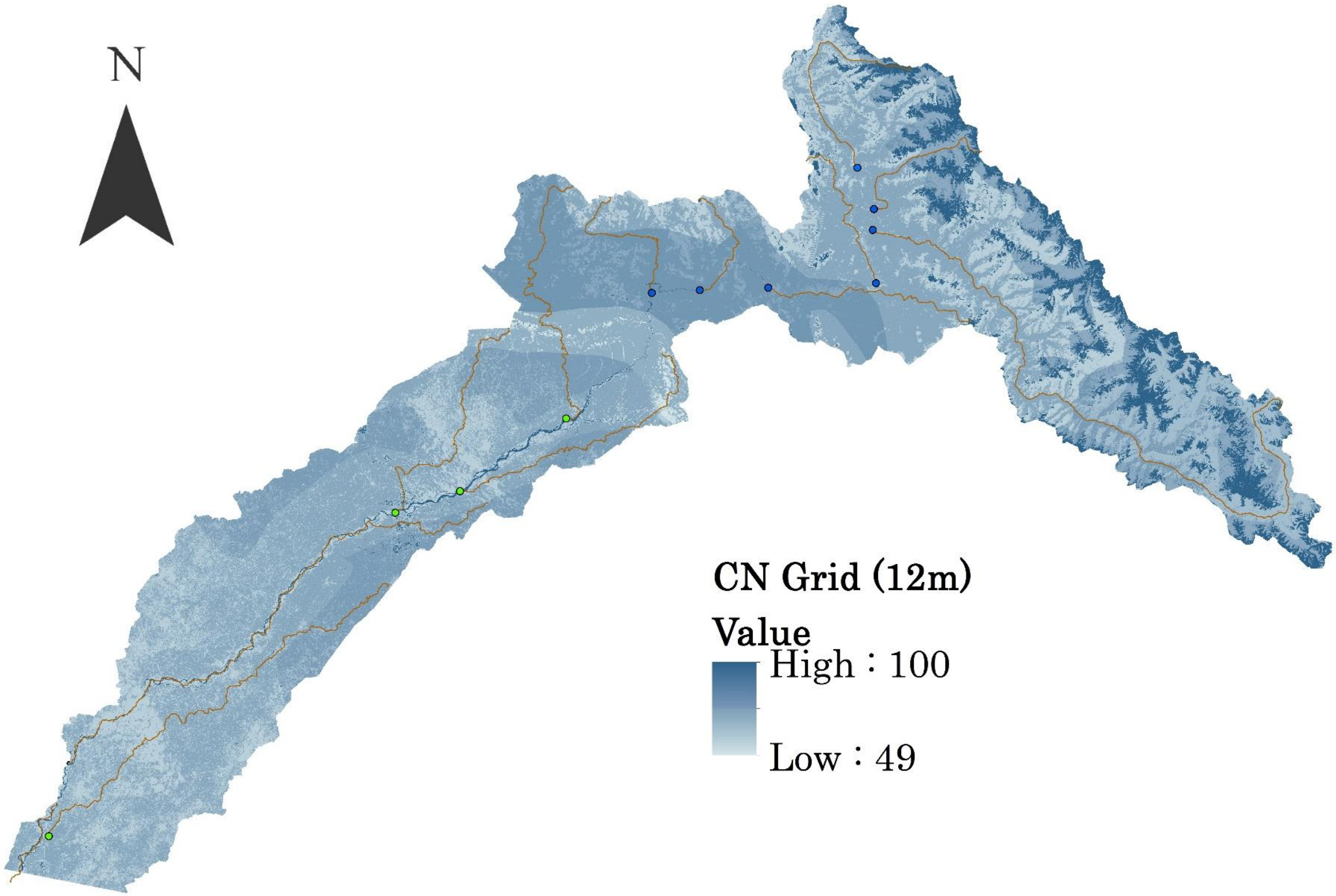


Figure 14: Pervious Percent

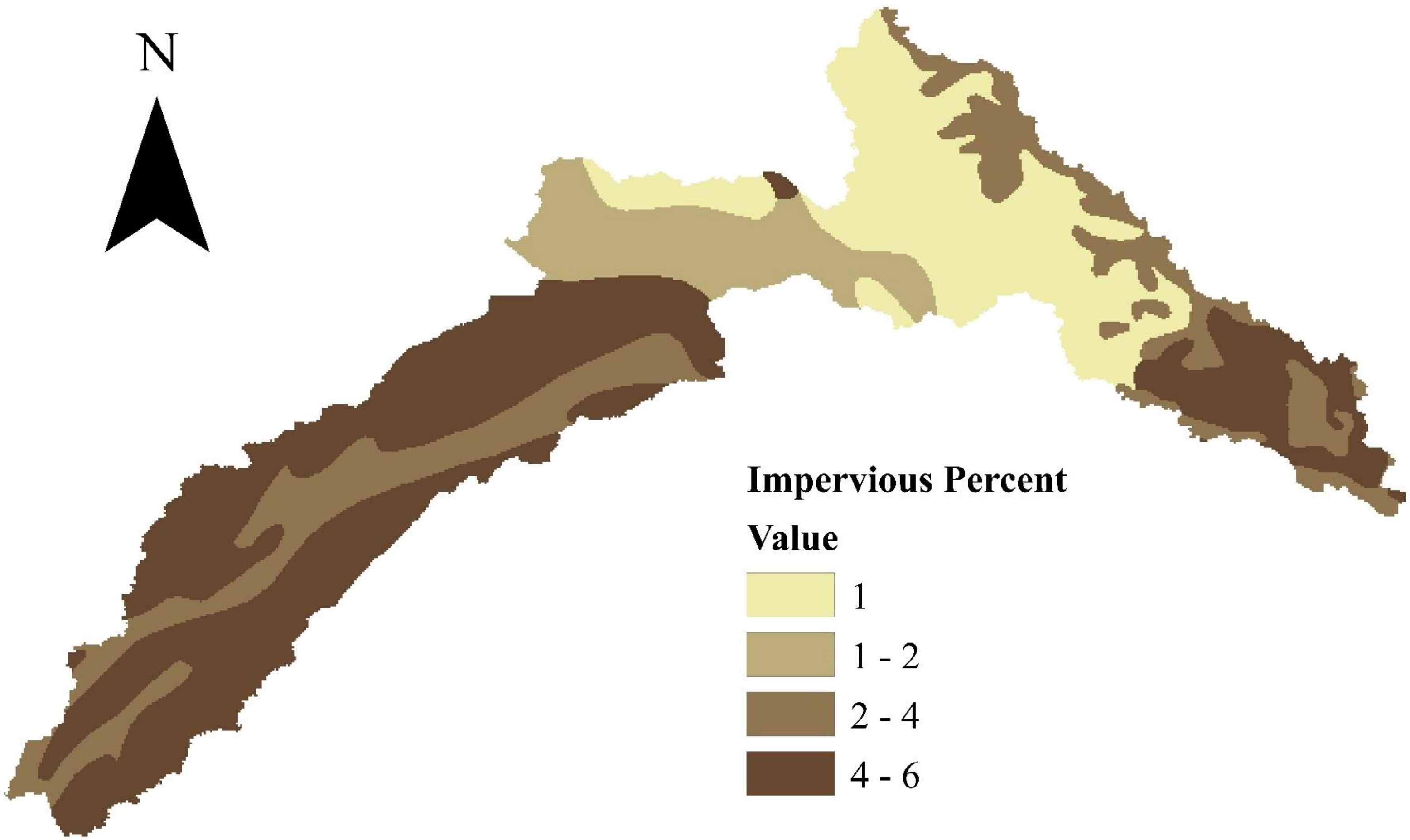


Figure 15: Impervious Percent

Hydro-Meteorological Datasets:

Hydro-Meteorological datasets are either model based or observed, TRMM-3B42 rainfall data is Real Time (RT) and APHRO_MA is secondary source Regional Climate Model (RCM) of Monsoon Asia on minimum equal resolution of 25km grid.

Area-Average Time Series:

Script in OpenGrADS convert with object of time limit in 366 day for leap year uncertain parameter object of precipitation with loop in minimum and maximum latitude and longtiude and take 'aave' function for Area-Average Time Series. Both rainfall datasets of TRMM-3B42 and APHRO_MA are in netCDF with certain parameter on daily time scale, information from 2005-2013 is extracted in excel tabular format to make it readable for HEC-HMS through HEC-DSS input to perform calibration and validation, no observed rainfall datasets are avaiable for bias correction due to transboundary of chenab basin. Hence, intercomparison of satellite base and interpolated information utilized for accuracy assessment.

Annual rainfall correlation of TRMM with APHRO indicates increase of 19% for model calibration period from 2005-2009 and 11% increase for validation period of 2010-2013, the overall 17% increase for nine years in case of TRMM. While seasonal rainfall correlation in Rabi season shows 35% decrease for TRMM and 50% increase in Kharif season with APHRO.

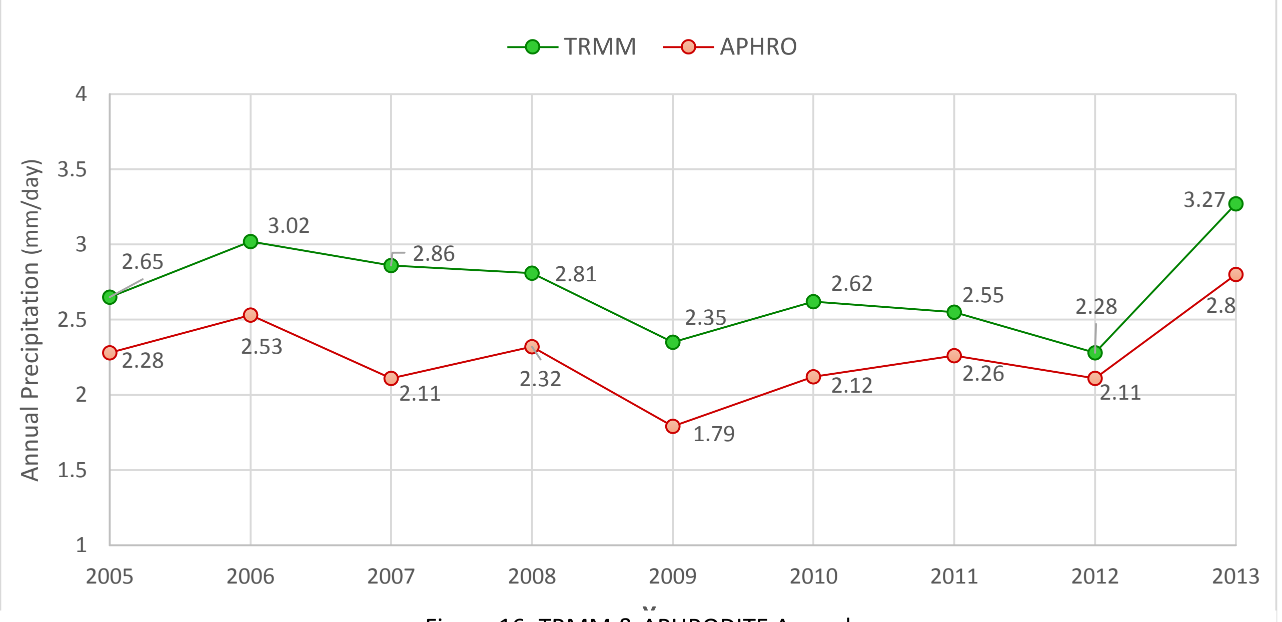


Figure 16: TRMM & APHRODITE Annual

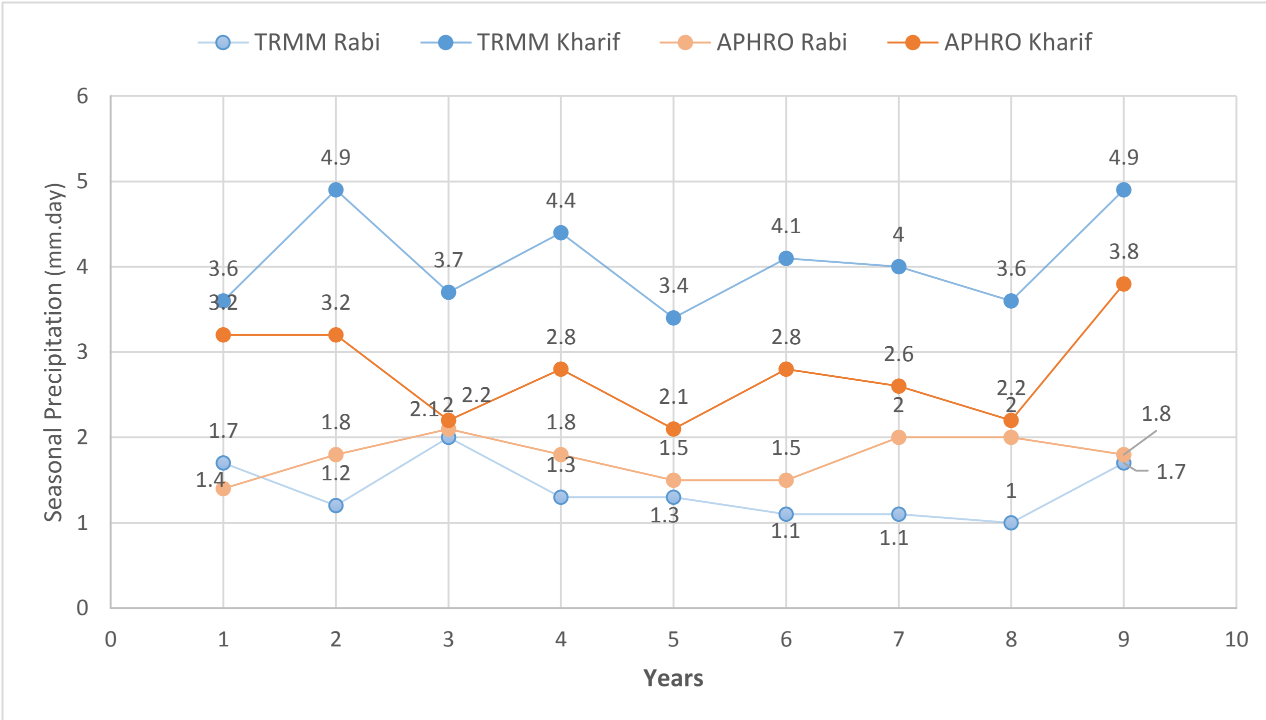


Figure 17: TRMM & APHRODITE Seasonal

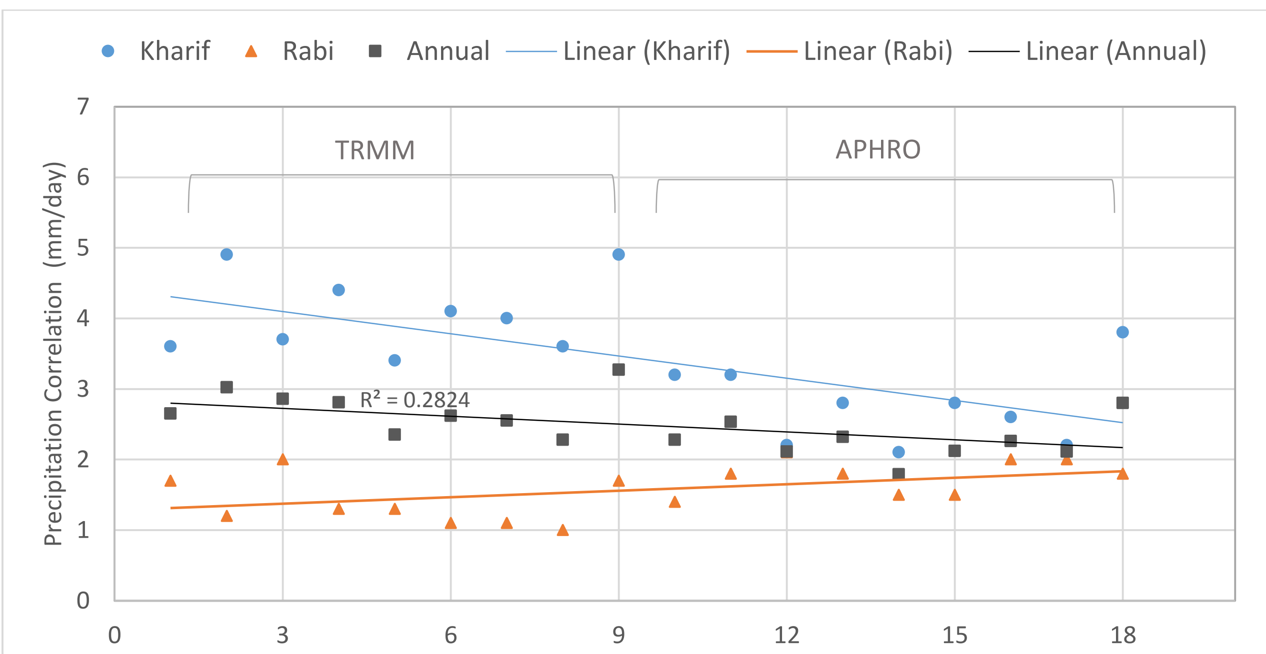


Figure 18: TRMM & APHRODITE Correlation

Linear Correlation shows trendline shift from APHRO (right) to TRMM (left) with positive and negative as upside and downside. Seasonal correlation is high as positive in case of Kharif and negavtive for rabi while low to no correlation in annual precipitation.

Pseudo-Distributed Approach:

Chenab basin with pseudo distributed approach carry each lump formation of control point for hydrological assessment, Three Pakistani structures in downstream sub-basin Marala, Khanki and Qadirabad. Trimmu sub-basin is not included in study due to its confluence with Jhelum at upstream.

Multi-Criteria Parameter Estimation:

Parameters shift in process within its boundary limits for lumped formation having certain and uncertain criteria for estimation of model. Certain parameters are constant for actual geospatial indication while uncertain parameter change in limits to force processes of hydrology. Rainfall-runoff analysis for goodness-of-fit coefficient determination take these parameters to evaluate pseudo-distributed approach in Chenab basin with multi-criteria decision making process. Certain parameters remain silent within lumped (sub-basin) while uncertain fluctuate for lower and upper bound values have area, slope, longest flow path and curve number, impervious percent, lag time respectively. Uncertain boundary limits are extracted from attributes of raster datasets, initial conditions are applied through mean value. Uncertain parameters shift with percentage change (+/-) except for lag-time which change with 'C' in minimum and maximum values, these thresholds keep parameter in boundary limit during calibration of model.

Relationship between certain and uncertain parameters differentiate terrain property for runoff estimation with sub-basin comparison for high slope upstream and downstream state has low lag time and impervious percent while high curve numbers, Area and longest flow path from more than 2000 SQ.KM and 100 km sub-basins comparison indicate 53% and 49% decrease in lag time, impervious percent respectively while 4% increase in curve number demonstrate control of Chenab River.

Observed streamflow data of three above mentioned control point on daily basis to calibrate HEC-HMS for two rainfall dataset's accuracy assessment is estimated through 'Coefficient of Determination' (R^2), Nash-Sutcliffe (NSE) and P-BIAS. Initial condition for model estimate weak or low Influence between observed and simulated streamflow, uncertain parameter has been shift from mean values to either increment or decrement phase. Max variation of -28% and +40% in mean CN and impervious percent values, Lag time with constant -60% from "C=15" calibrate model from year 2005 to 2009 highlighted in light grey of Table 1 , Then same parameter set for validation period of 2010 to 2013 for both rainfalls in incremental form of 24 hour.

Sub-Basin		Certain			Uncertain								
		Area	Slope	LFP	Curve Number			Impervious %			Lag Time-min		
No	Name	SQ.KM	%	Km	Min	Mean	Max	Min	Mean	Max	Min	C=6	Max
1	Dul-Hasti	10747	65.51	345	49	72.49	100	1	3.14	5	8052.9	20132.2	30198.4
2	Pakal-Dul	1120	69.84	83	49	75.00	100	1	2.50	4	2289.4	5723.5	8585.3
3	Bursur	2960	62.19	118	49	70.62	100	1	1.87	4	2163.3	5408.4	8112.7
4	Ratle	1120	66.79	86	49	68.04	100	1	1.00	1	1825.3	4563.3	6844.9
5	Baglihaar	2708	61.59	111	49	70.67	100	1	1.36	2	3236.1	8090.2	12135.3
6	Sawalkot	1570	59.92	69	49	72.53	100	1	1.99	5	2669.2	6673.2	10009.8
7	Salal	1541	60.41	94	49	70.99	100	1	1.57	2	3132.5	7831.3	11747.0
8	Marala	4544	27.45	182	49	71.50	100	1	3.44	6	8485.3	21213.2	31819..9
9	Khanki	2624	7.07	161	49	67.88	100	3	4.38	6	9363.1	23407.8	35111.7
10	Qadirabad	2254	6.58	143	49	66.13	100	3	4.76	6	11093.9	27734.9	41602.4
11	Up-Trimmu	5198	4.86	278	49	67.28	100	3	4.00	5	32475.5	81188.9	121783.4

Table 4: Sub-basin Parameter (Uncalibrated)

Sub-Basin		Certain			Uncertain												
		Area	Slope	LFP	Curve Number					Impervious %					Lag Time-min		
No	Name	SQ.KM	%	Km	Min	-28%	-25%	Mean	Max	Min	-25%	Mean	+40%	Max	-33%	C=6	+60%
1	Dul-Hasti	10747	65.51	345	49	52.2	54.36	72.49	100	1	2.4	3.14	4.4	5	8052.9	20132.2	30198.4
2	Pakal-Dul	1120	69.84	83	49	54.0	56.25	75.00	100	1	1.9	2.50	3.5	4	2289.4	5723.5	8585.3
3	Bursur	2960	62.19	118	49	50.8	52.96	70.62	100	1	1.4	1.87	2.6	4	2163.3	5408.4	8112.7
4	Ratle	1120	66.79	86	49	49.0	51.03	68.04	100	1	1.0	1.00	1.0	1	1825.3	4563.3	6844.9
5	Baglihaar	2708	61.59	111	49	50.9	53	70.67	100	1	1.0	1.36	1.9	2	3236.1	8090.2	12135.3
6	Sawalkot	1570	59.92	69	49	52.2	54.39	72.53	100	1	1.5	1.99	2.8	5	2669.2	6673.2	10009.8
7	Salal	1541	60.41	94	49	51.1	53.24	70.99	100	1	1.2	1.57	2.2	2	3132.5	7831.3	11747.0
8	Marala	4544	27.45	182	49	50.0	53.62	71.50	100	1	2.6	3.44	4.8	6	8485.3	21213.2	31819..9
9	Khanki	2624	7.07	161	49	49.0	50.91	67.88	100	3	3.3	4.38	6.0	6	9363.1	23407.8	35111.7
10	Qadirabad	2254	6.58	143	49	49.0	49.59	66.13	100	3	3.6	4.76	6.0	6	11093.9	27734.9	41602.4
11	Up-Trimmu	5198	4.86	278	49	49.0	50.46	67.28	100	3	3.0	4.00	5.0	5	32475.5	81188.9	121783.4

Table 5: Sub-basin Parameters (Calibrated)

Chapter 4
Result & Discussion

Model Projections:

Annual and seasonal correlation through regression analysis of TRMM and APHRO project streamflow which calibrated in HEC-HMS for accuracy assessment of Chenab basin in pseudo-distributed approach for Marala, Khanki and Qadirabad control point.

Annual projection relates 3 efficiency constant of R^2, NSE and P-BISE, At Marala Headworks TRMM & APHRO calibration from 2005-2009 '_C' of (TRMM_C & APHRO_C) results (R^2, NSE, PBIAS) as (0.72, 0.53, -28) & (0.67, 0.66, -3) respectively, while validation from 2010-2013 '_V' of (TRMM_V & APHRO_V) results (0.74, 0.81, -6) & (0.62, 0.57, -13) respectively. Khanki Headworks calibration of TRMM & APHRO results in (R^2, PBIAS) as (0.53, -104) & (0.56, -64) respectively, while validation results (0.81, -87) & (0.68, -62) respectively. Qadirabad Barrage calibration of TRMM & APHRO results in (R^2, PBIAS) as (0.47, -67) & (0.45, -35) respectively, while validation results (R^2, PBIAS) as (0.74, -67) & (0.64, -44) respectively.

Two seasons of Rabi and Kharif are major impact factor hydro-meteorological consideration of Chenab basin evaluated for TRMM & APHRO rainfall datasets with efficiency constants of R^2 & PBIASE which results Rabi season for Marala Headworks, Khanki Headworks and Qadirabad Barrage in two simulation intervals from 2005-2009 '_C' and 2010-2013 '_V' of (TRMM_C, TRMM_V, APHRO_C, APHRO_V) as (0.04, 0.11, 0.01, 0.05) & (-9, -3, -27, -52), (0.15, 0.14, 0.16, 0.01) & (-52, -65, -76, -142) and (0.18, 0.16, 0.11, 0.12) & (-14, -13, -32, -66) respectively, while accuracy constant R^2 results in Kharif season for Marala Headworks, Khanki Headworks and Qadirabad Barrage in two simulation intervals from 2005-2009 '_C' and 2010-2013 '_V' of (TRMM_C, TRMM_V, APHRO_C, APHRO_V) as (0.74, 0.71, 0.77, 0.78) & (-36, -30, 7, 9), (0.61, 0.8, 0.63, 0.78) & (-132, -95, -58, -36) and (0.52, 0.58, 0.54, 0.71) & (-100, -92, -36, -33) respectively.

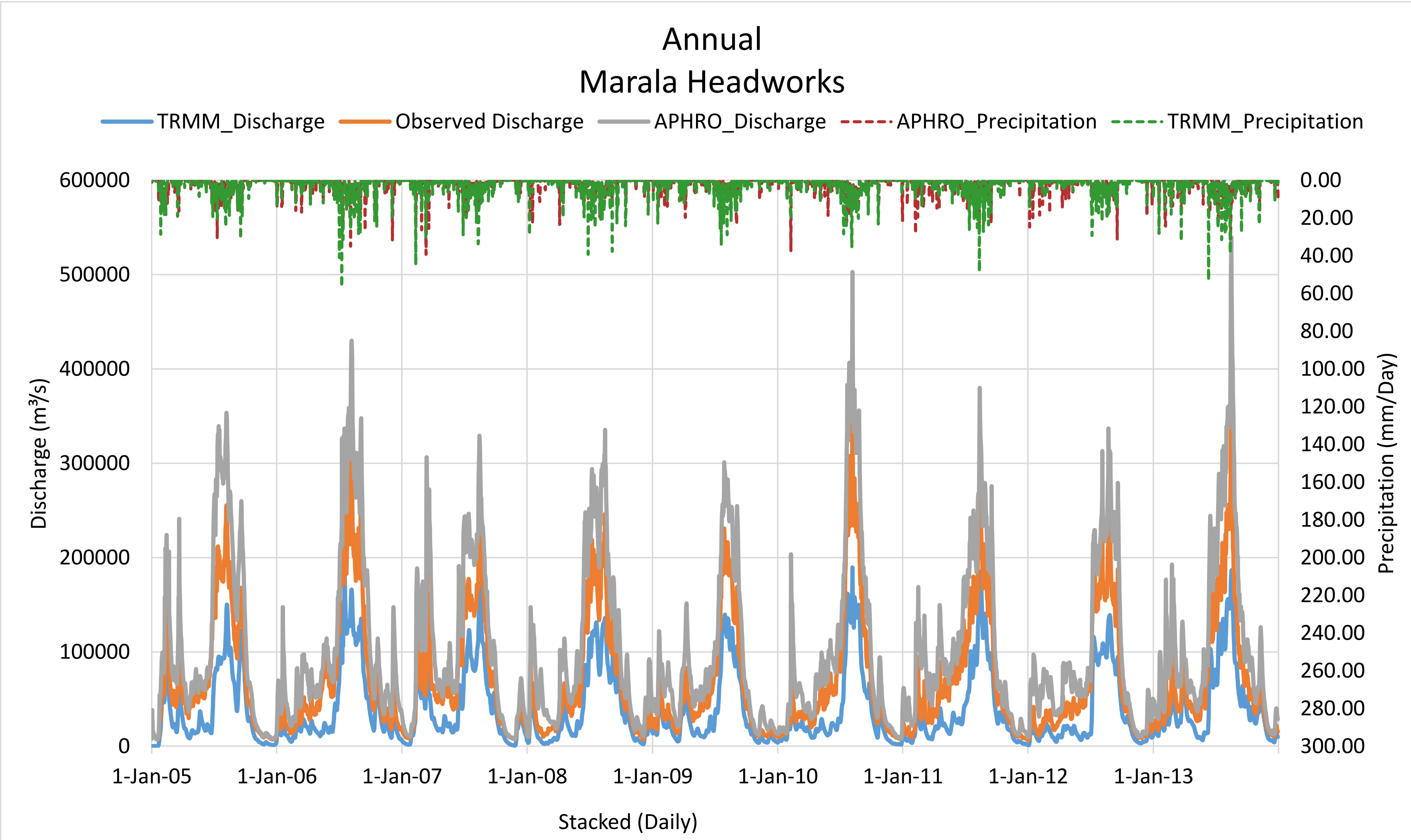


Figure 19: Annual Hydrograph (Marala Headworks)

Figure 20: Annual Performance (Marala Headworks)

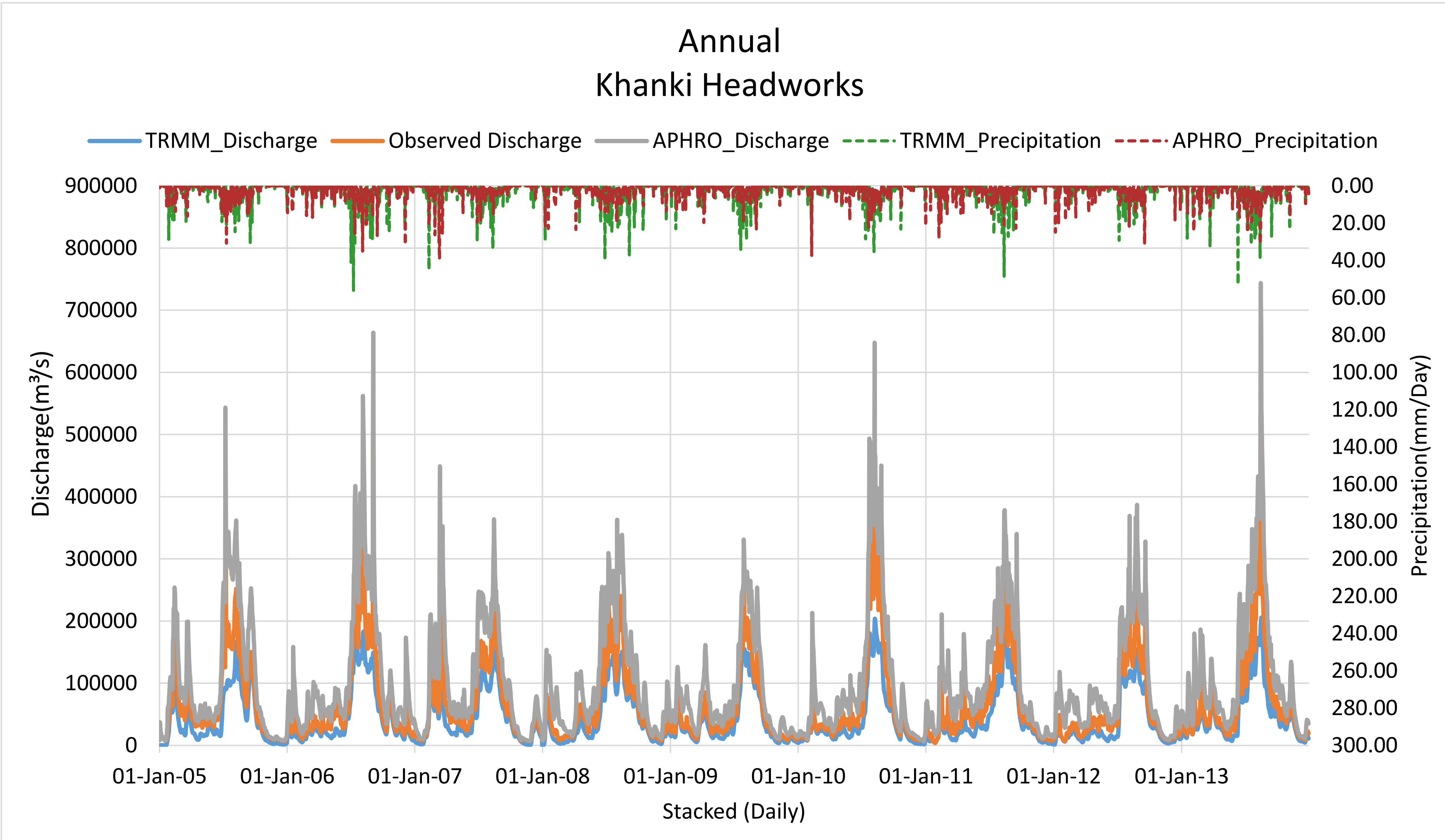


Figure 21: Annual Hydrograph (Khanki Headworks)

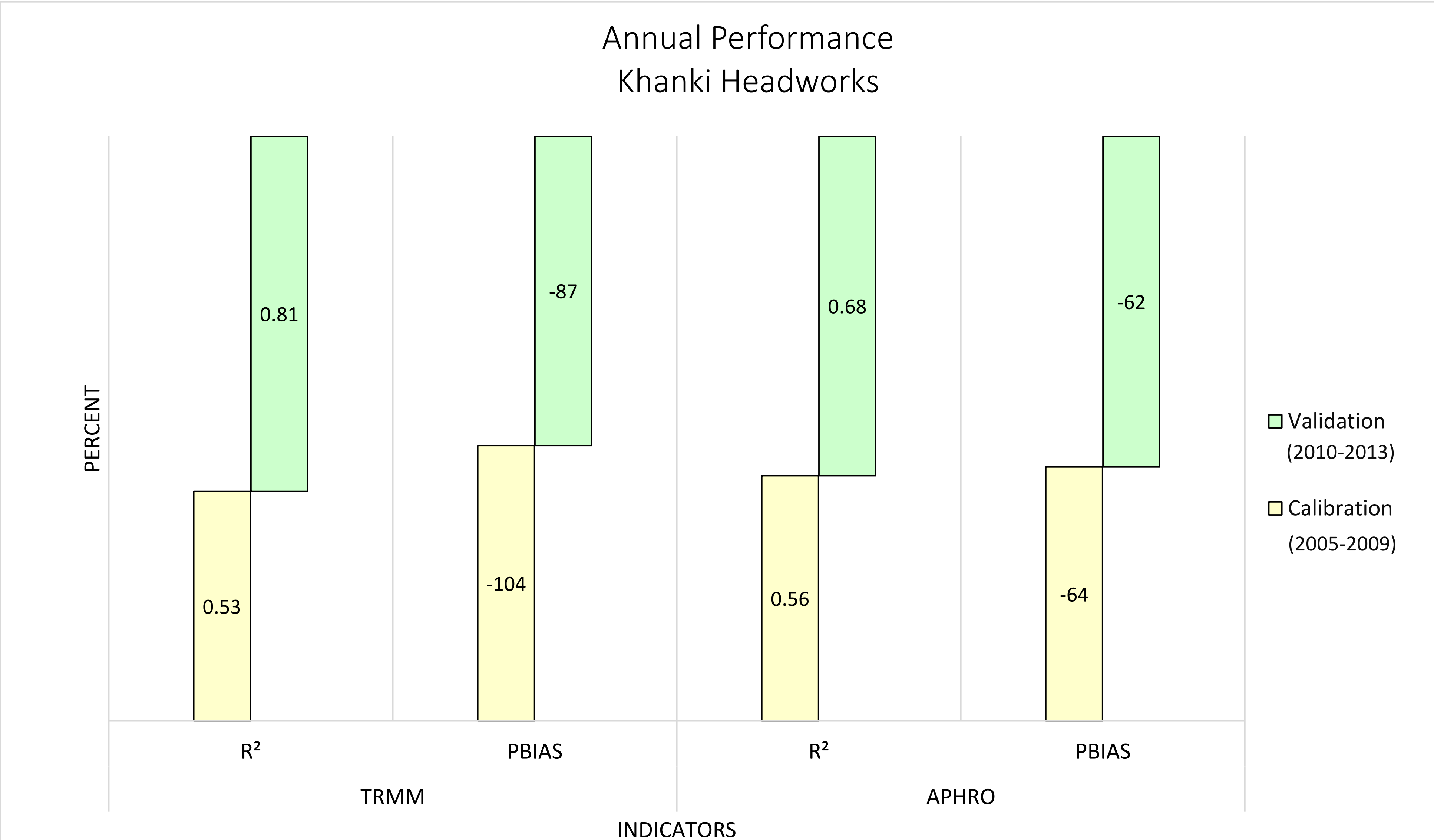


Figure 22: Annual Performance (Khanki Headworks)

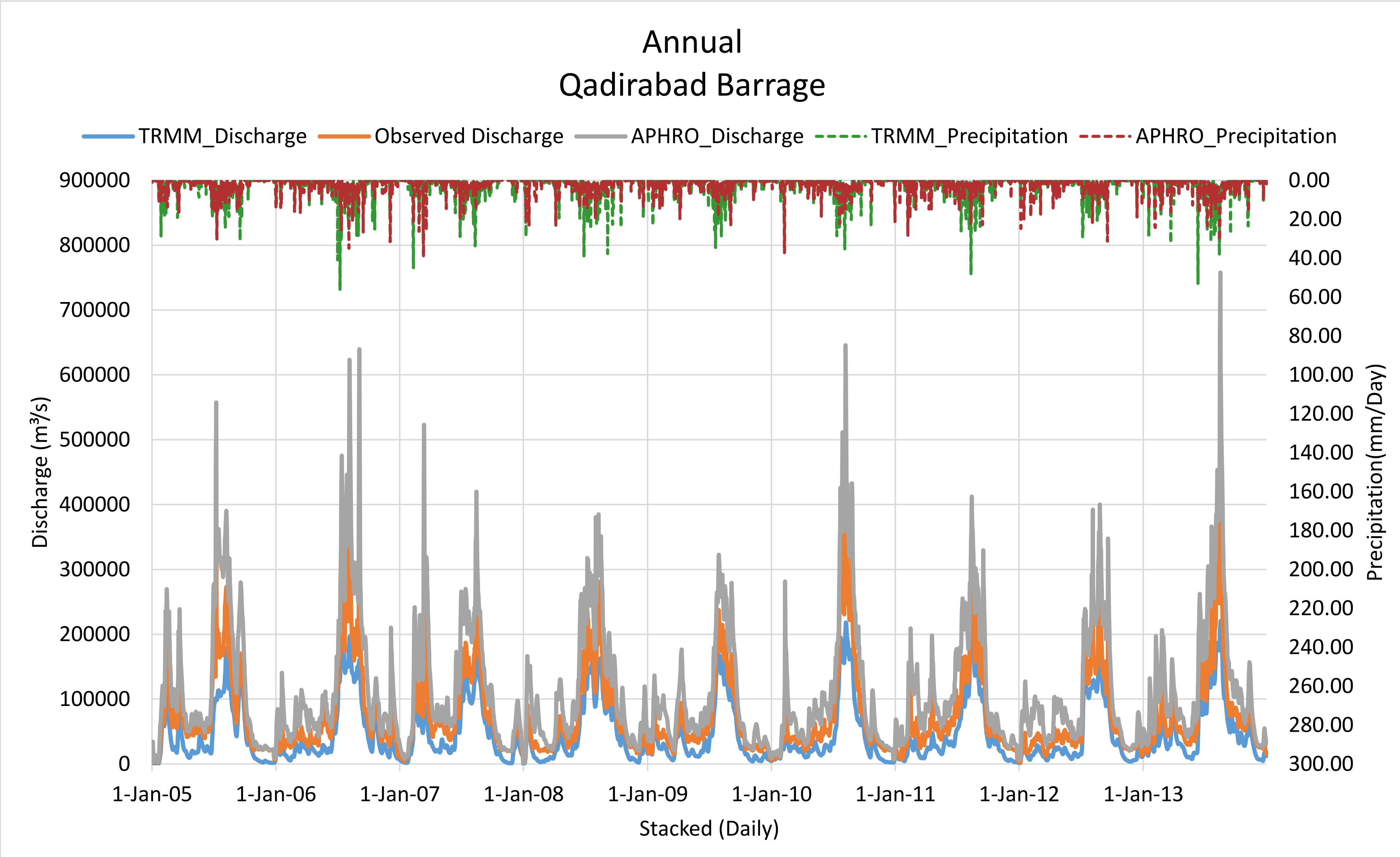


Figure 23: Annual Hydrograph (Qadirabad Barrage)

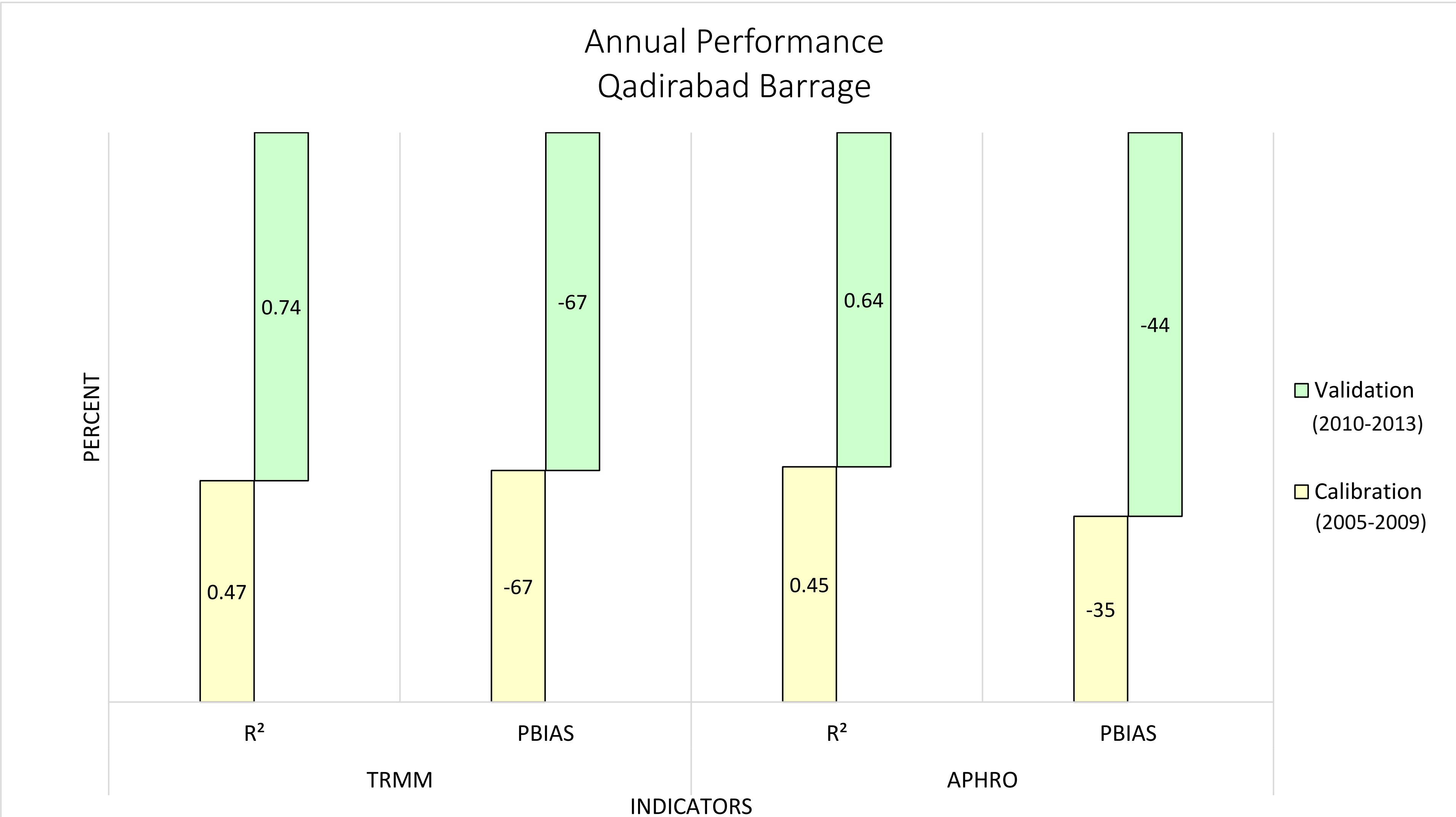
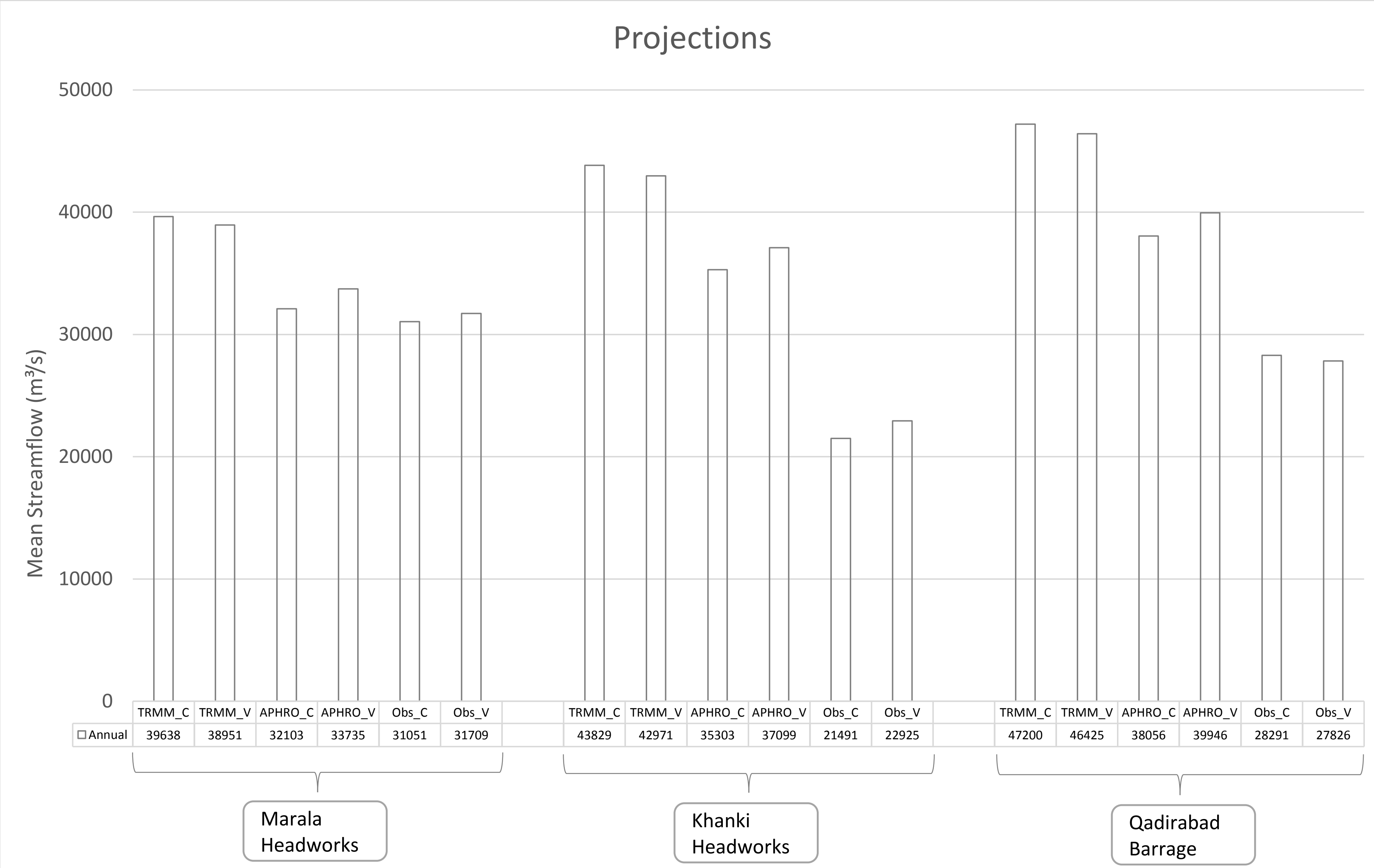


Figure 24: Annual Performance (Qadirabad Barrage)



	TRMM_C	TRMM_V	APHRO_C	APHRO_V	Obs_C	Obs_V
Marala Headworks – Annual	39638	38951	32103	33735	31051	31709
Khanki Headworks – Annual	43829	42971	35303	37099	21491	22925
Qadirabad Barrage – Annual	47200	46425	38056	39946	28291	27826

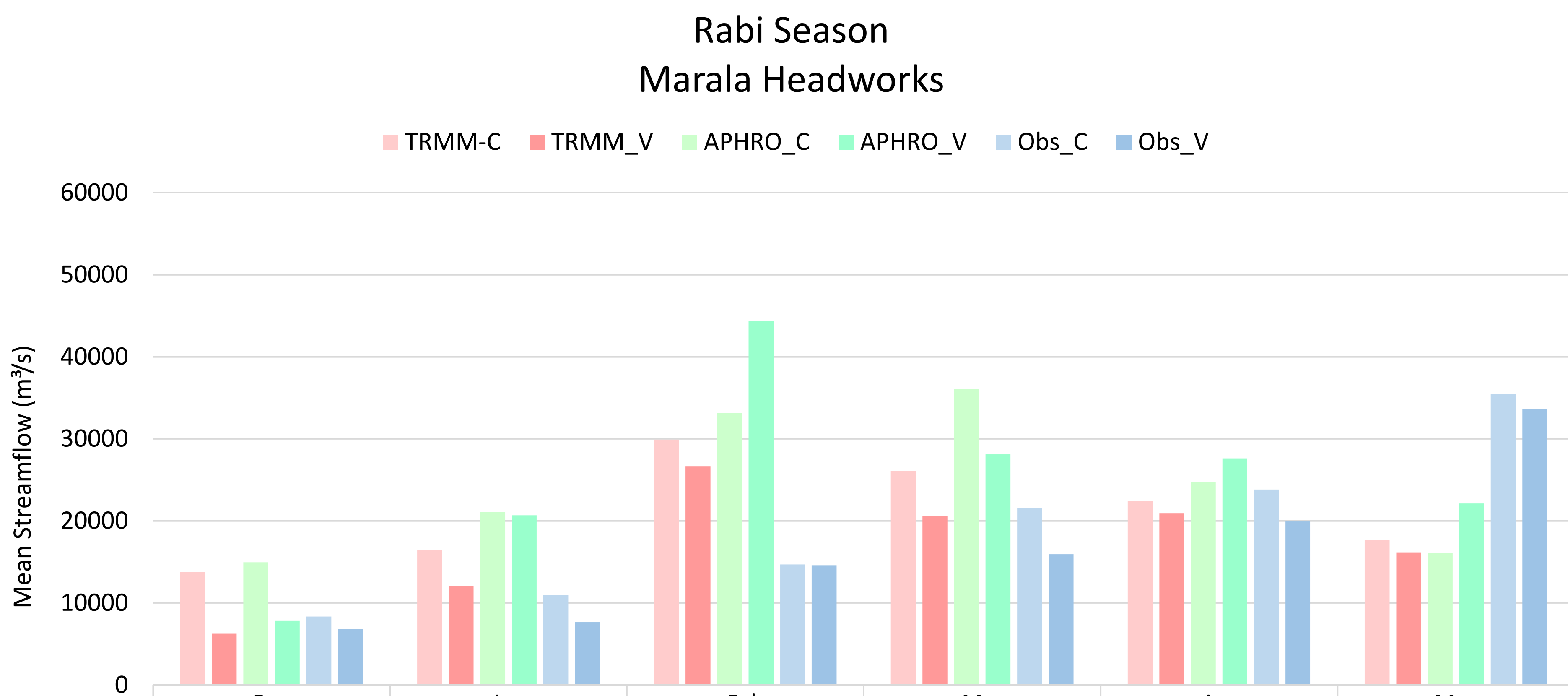
Figure 25: Annual Projections

Annual Trend Analysis:

Annual streamflow from TRMM and APHRO compare on mean daily basis which indicate trends of R^2 shifts from Qadirabad Barrage to Marala Headworks with inverse distance weighting interpolation for accuracy assessment in case of TRMM_V, while P-BIAS shifts from Khanki Headworks towards Qadirabad Barrage in less quantity and more favor towards Marala Headworks for APHRO_C. Maximum accuracy of HEC-HMS model is achieve for TRMM rainfall while APHRO make it more favorable for future climate projections.

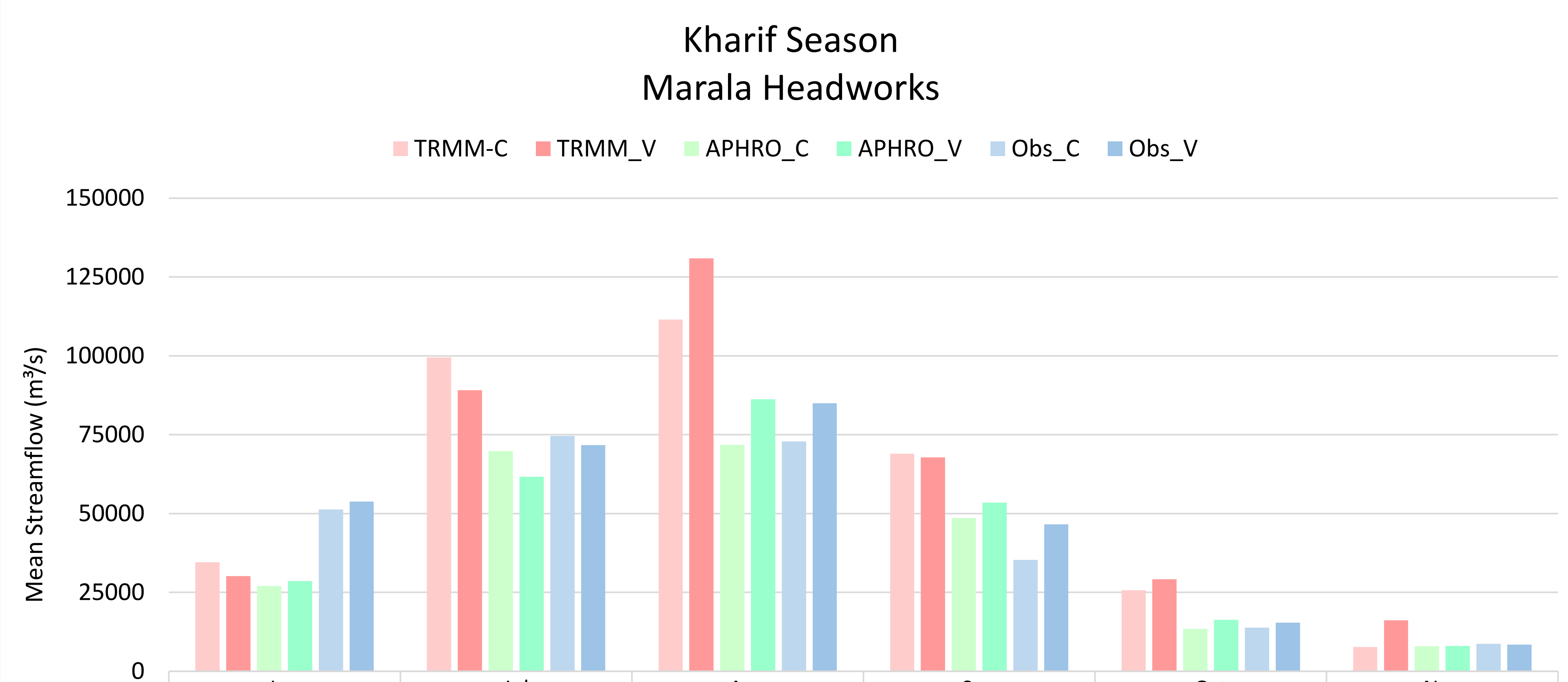
Annual streamflow efficiency predictor estimate Influence of upstream control points on downstream state on mode-1 as Marala Headwork is situated just downstream of LOC (Line of Control), accuracy predictor of R^2 estimate low correlation for TRMM_C on the other hand APHRO_C make high dependency of simulated streamflow with observed, while in stage of TRMM_V and APHRO_V 2% and 7% increase and decrease on independent observed streamflow. PBIAS predictor shows less favor of simulated with observed streamflow for TRMM_C in contrast to APHRO_C, while increase of 5% and decrease of 3% for TRMM_V & APHRO_V. Upper Jhelum Link (U.J.L) canal from Mangla reservoir to Khanki headwork estimate accuracy and favism for both TRMM_C & APHRO_C towards TRMM_V & APHRO_V in 28% and 12%, 17% and 2% increment form. Link (R.Q.L) canal from Rasul barrage to Qadirabad Barrage make APHRO_V of 9% less favorable and kept same for TRMM_C & TRMM_V, while increase in accuracy 27% and 19% for TRMM_V and APHRO_V.

Streamflow per day projection indicate more reliability of APHRODITE dataset for irrigation as required discharge is 1290 cumec in Marala Headworks is achieved for APHRO_C with 1338 cumec difference of 48 cumec and 67% accuracy, opposite to high peak flood of 1651 cumec is case for TRMM_C increment of 361 cumec with 72% accuracy as accumulation of droplets are greater due to less time span of TRMM satellite which has 90 minute capturing capability with 1440 minute of APHRODITE. Khanki Headworks and Qadirabad Barrage shows increase of 883, 781 cumec for TRMM and 583, 456 cumec for APHRODITE datasets from design discharge respectively.



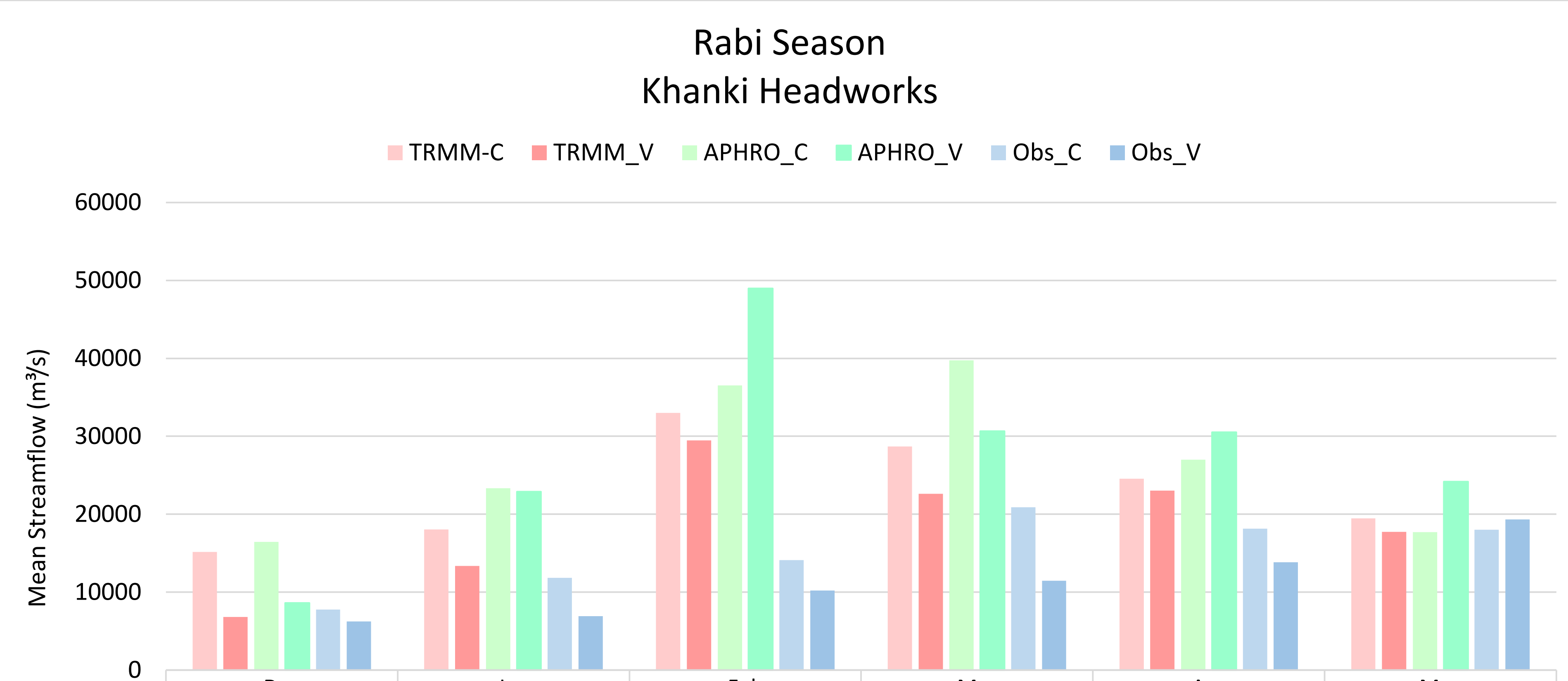
	Dec	Jan	Feb	Mar	Apr	May
TRMM-C	13770	16466	29917	26083	22404	17702
TRMM_V	6250	12083	26676	20605	20936	16176
APHRO_C	14956	21083	33159	36067	24757	16106
APHRO_V	7826	20664	44347	28121	27629	22135
Obs_C	8328	10964	14689	21524	23817	35451
Obs_V	6834	7639	14606	15937	19912	33611

Figure 26: Rabi Season Indices (Marala Headworks)



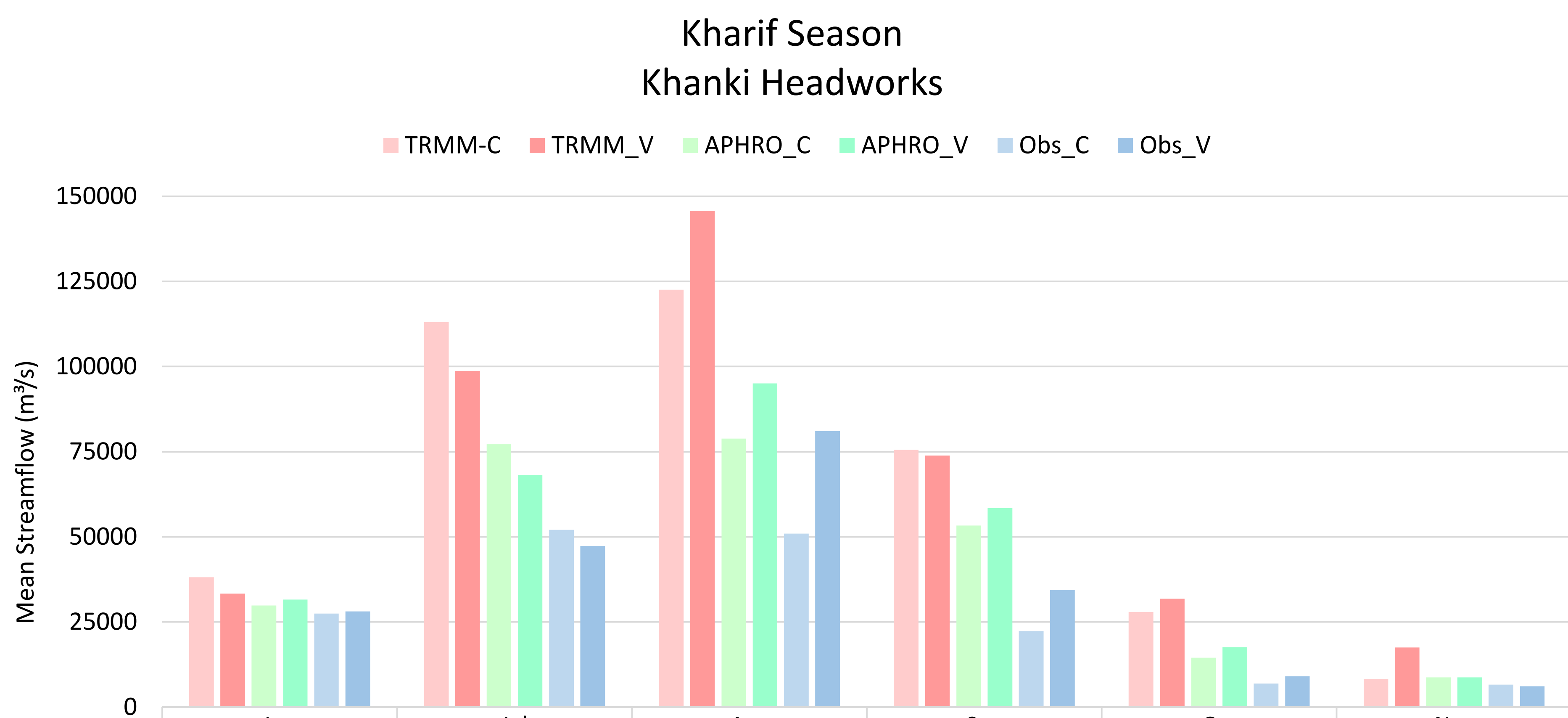
	Jun	Jul	Aug	Sep	Oct	Nov
TRMM-C	34550	99467	111481	68972	25714	7695
TRMM_V	30145	89122	130875	67791	29176	16114
APHRO_C	27021	69762	71756	48593	13449	7946
APHRO_V	28575	61643	86250	53453	16284	8026
Obs_C	51336	74575	72857	35326	13866	8655
Obs_V	53816	71691	84967	46616	15425	8416

Figure 27: Kharif Season Indices (Marala Headworks)



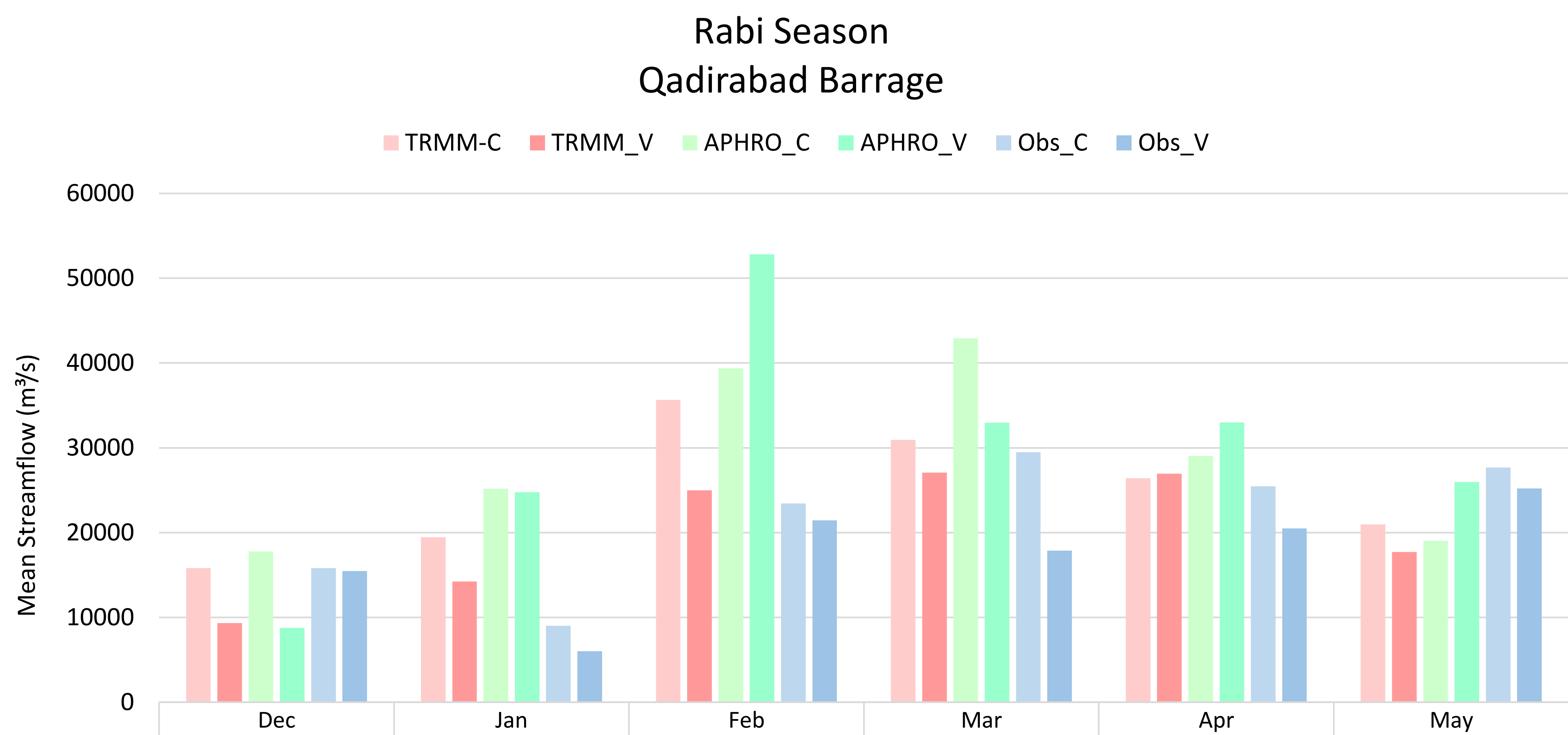
	Dec	Jan	Feb	Mar	Apr	May
TRMM-C	15165	18039	33003	28699	24540	19462
TRMM_V	6832	13365	29460	22610	23038	17723
APHRO_C	16456	23328	36521	39761	26999	17693
APHRO_V	8609	22893	48983	30671	30531	24188
Obs_C	7777	11822	14110	20901	18155	18022
Obs_V	6257	6904	10194	11467	13825	19322

Figure 28: Rabi Season Indices (Khanki Headworks)



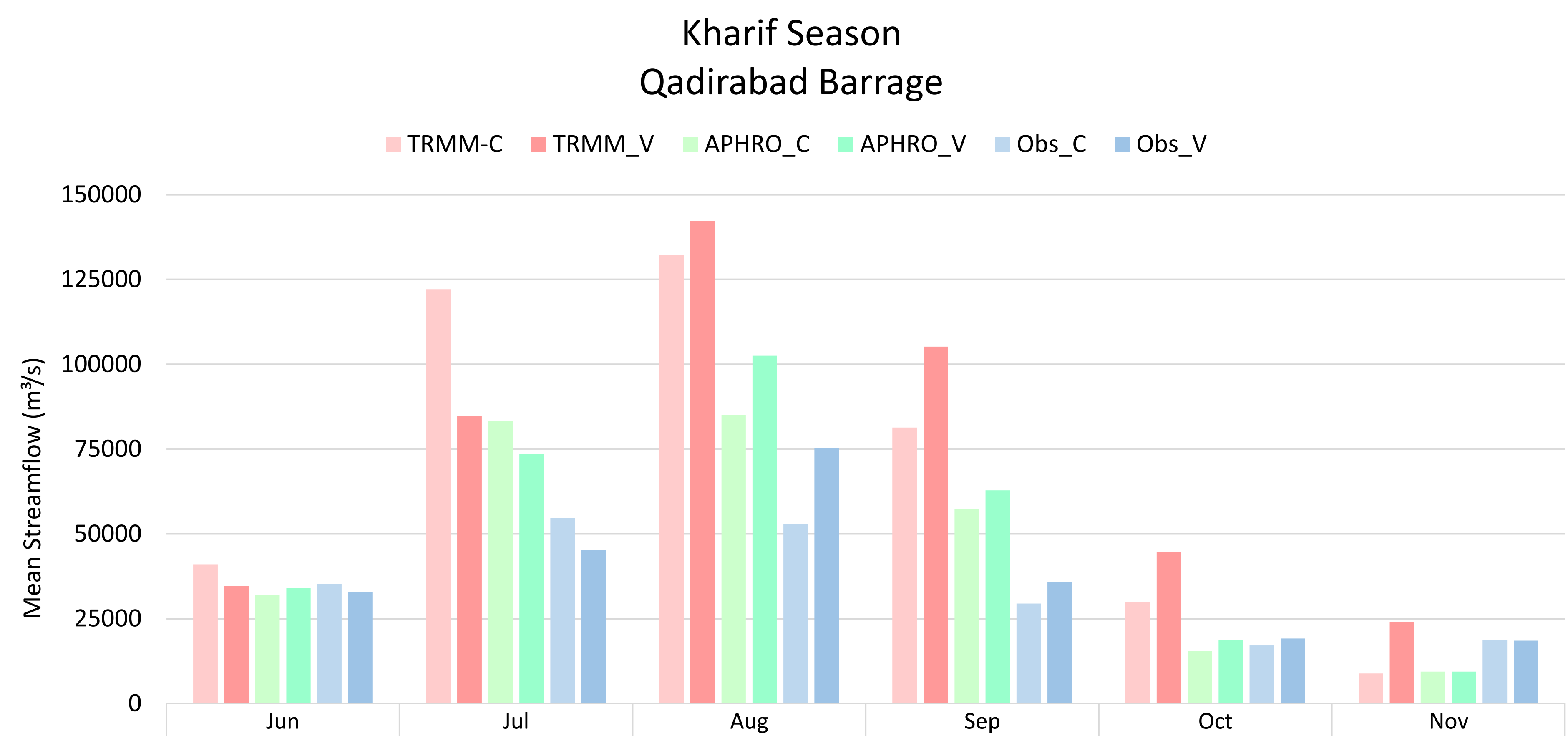
	Jun	Jul	Aug	Sep	Oct	Nov
TRMM-C	38144	113025	122534	75525	27905	8281
TRMM_V	33316	98691	145741	73892	31813	17520
APHRO_C	29803	77151	78831	53269	14461	8724
APHRO_V	31525	68195	95022	58403	17580	8737
Obs_C	27465	52061	50928	22301	6933	6573
Obs_V	28070	47300	81072	34438	9021	6110

Figure 29: Kharif Season Indices (Khanki Headworks)



	Dec	Jan	Feb	Mar	Apr	May
TRMM-C	15817	19449	35646	30935	26419	20964
TRMM_V	9328	14242	24986	27077	26967	17733
APHRO_C	17778	25188	39378	42910	29033	19033
APHRO_V	8767	24768	52832	32966	32986	25974
Obs_C	15812	9032	23440	29476	25466	27677
Obs_V	15459	6032	21444	17873	20512	25217

Figure 30: Rabi Season Indices (Qadirabad Barrage)



	Jun	Jul	Aug	Sep	Oct	Nov
TRMM-C	41068	122139	132113	81300	29947	8851
TRMM_V	34680	84866	142271	105178	44536	24014
APHRO_C	32091	83334	85031	57372	15435	9388
APHRO_V	33997	73655	102549	62869	18765	9397
Obs_C	35230	54760	52834	29467	17136	18717
Obs_V	32873	45223	75367	35734	19151	18498

Figure 31: Kharif Season Indices (Qadirabad Barrage)

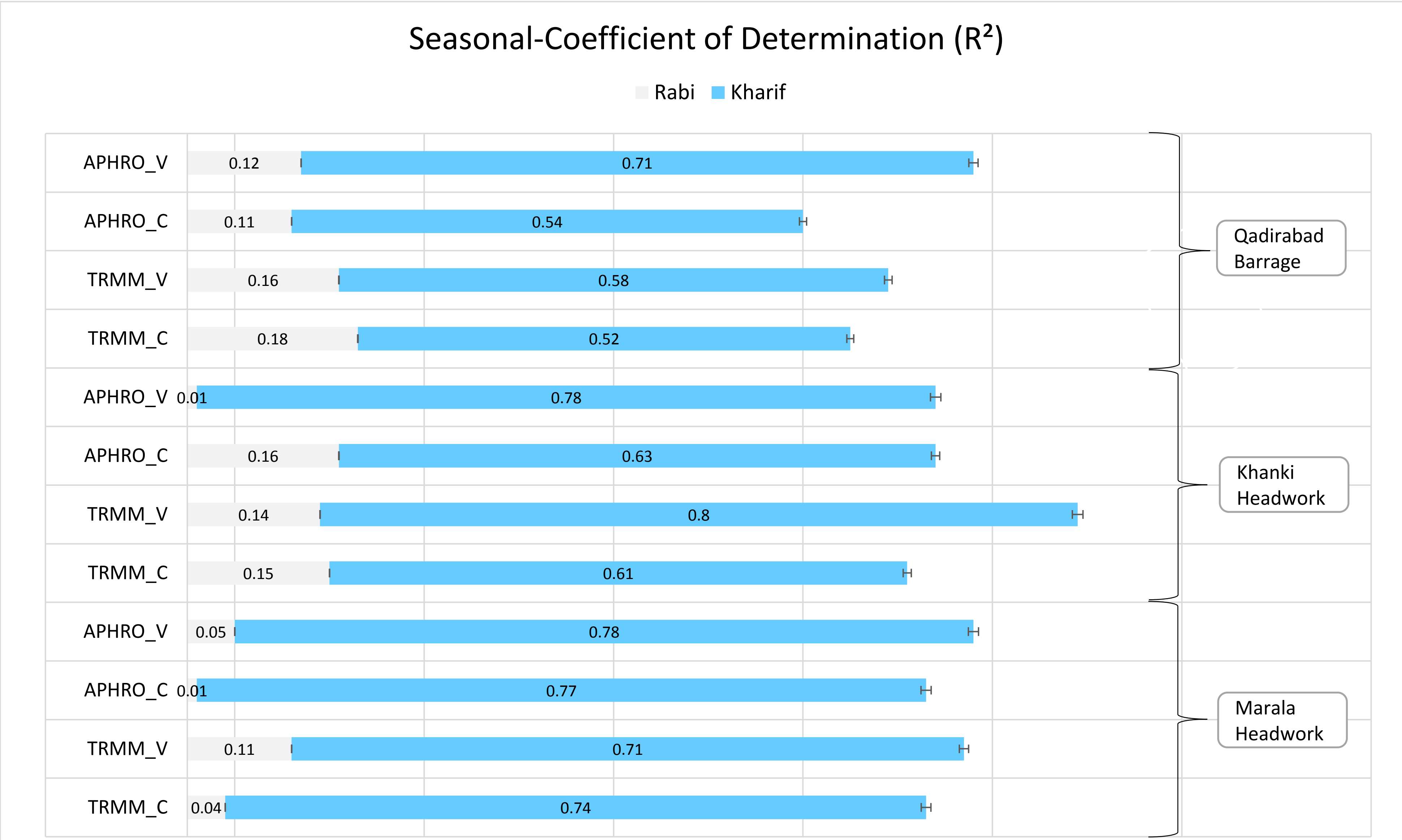


Figure 32: Coefficient of Determination

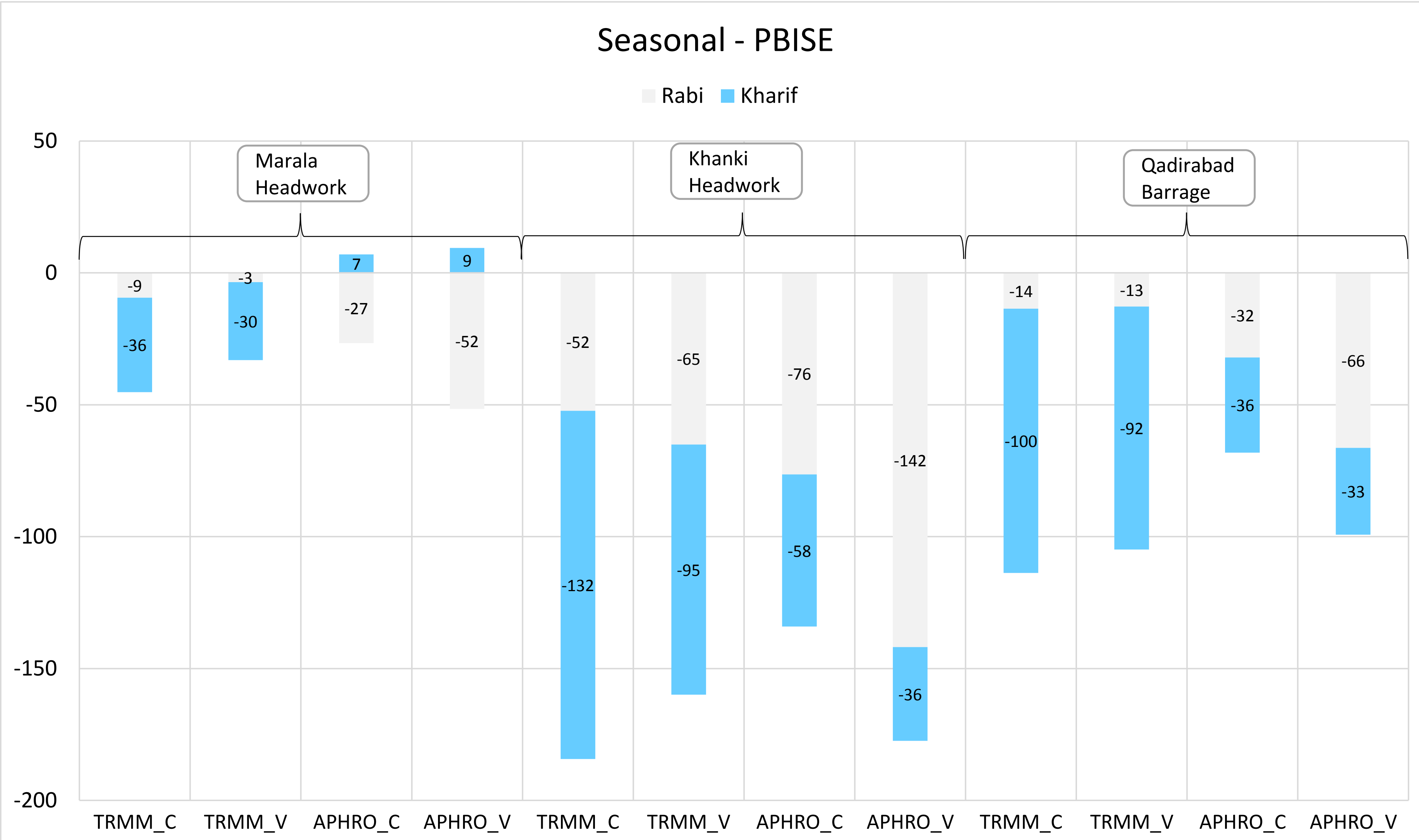


Figure 33: P-BIAS

Seasonal Trend Analysis:

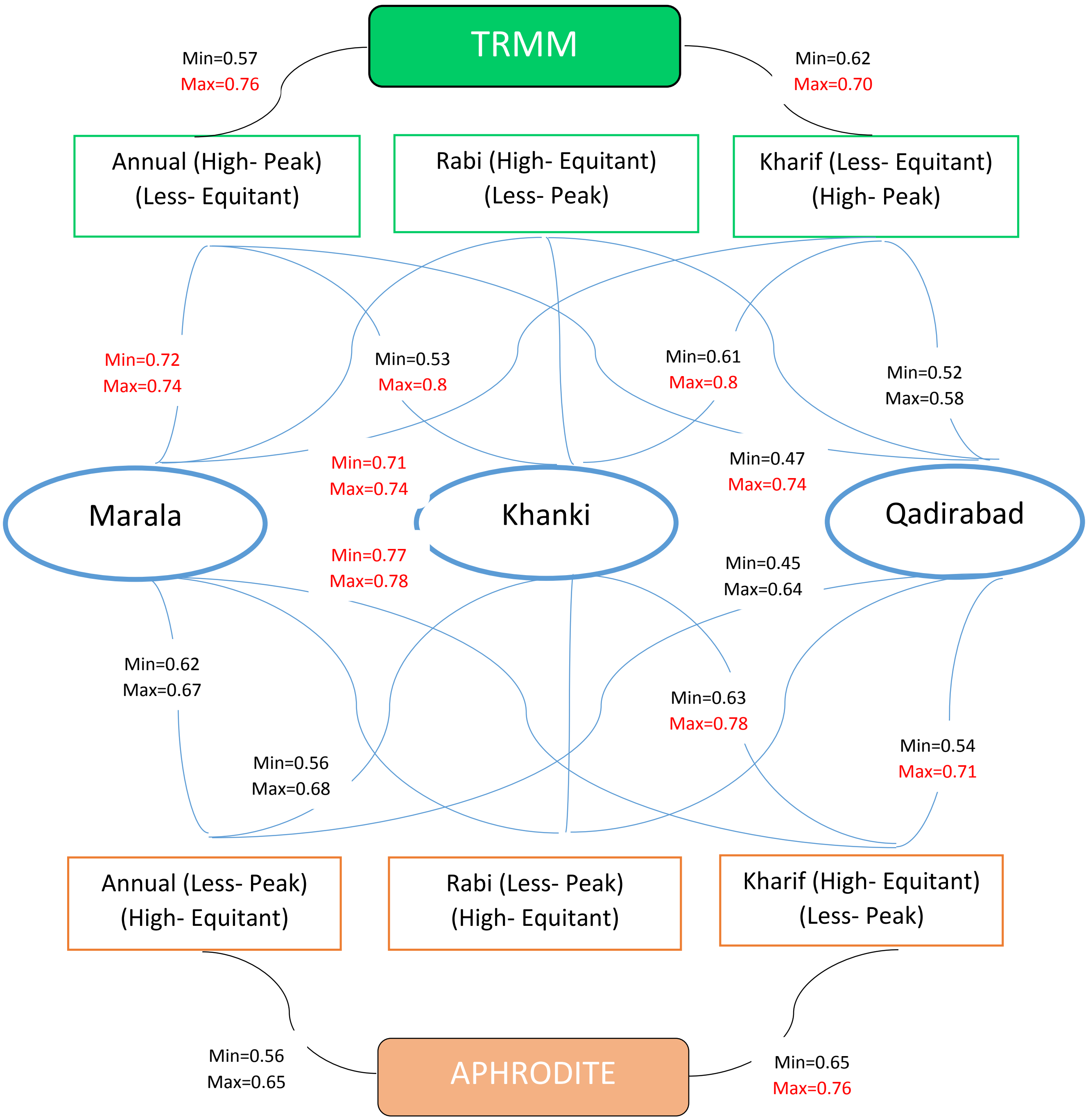
Streamflow from TRMM & APHRO compare on mean daily basis in Rabi (Dec-May) and Kharif (Jun- Nov) seasons for accuracy and favism trends which indicate accuracy of HEC-HMS shifts from Khanki Headworks of strong dependency 0.77 towards Qadirabad Barrage 0.60 in south-west direction and excel in north-east direction of 0.73 on Marala Headworks in case of TRMM_V while inverse distance weighting interpolation shows accuracy of APHRO_V from Marala Headworks towards downstream controls of Khanki Headworks and Qadirabad Barrage in 0.78 to 0.70 in Kharif season, very low dependency 0.10 is mean for all time spans in Rabi season. PBISE indicate favism of model for TRMM & APHRO in percentages shift from Marala Headworks of 6% towards Khanki Headworks and Qadirabad Barrage on -34% shows less numerical relationship for two downstream control points in case of APHRO_V for Kharif season.

Streamflow per day estimates Rabi season has high Influence of upstream control points on downstream state due to low dependency of overall 0.13 with R^2 accuracy predictor but high favism of TRMM_V for all three controls points of Marala Headworks, Khanki Headworks and Qadirabad Barrage differentiate 24, 307, 94 cumec for TRMM_V is strong case of (equitant) irrigation purposes, while in Kharif season high dependency of overall 0.70 on above mention controls with APHRO_V favism differentiate -184, 512, 521 cumec. High peak streamflow is APHRO_V in Rabi season while contraction to above TRMM_V indicate in Kharif season.

Ensemble Hydro-Meteorological Assessment:

HEC-HMS with pseudo-distributed approach project Hydro-meteorological datasets of TRMM & APHRODITE on accuracy predictors of R^2 & P-BIAS in three control points Marala Headworks, Khanki Headworks and Qadirabad Barrage of downstream state streamflow to evaluate Influence and control of upstream state from per day rainfall in incremental phase.

Accuracy predictors are in inverse relationship as R^2 (dependency) increase P-BIAS (Favism) decrease from ‘0’ as like to less likely in negative numeric and increase in positive. Due to terrain of transboundary in Chenab basin, it gives high authority of control and Influence on downstream state as best hydrological model assess streamflow trends discussed above in more refined lumped form predict TRMM as more dependent on observed while less dependency for APHRODITE as sensing time span is less for precedent dataset. Less and high favism for equitant and peak, TRMM is less favor of equitant to high favor of peak, while APHRODITE is shifting from less favor of peak to high favor of equitant phenomena. TRMM is more accurate in mode-1 while APHRODITE show less accuracy and favism in opposite direction which assess its Influence as high to low category.



Model Predictions:

Streamflow after projection of two hydro-meteorological dataset estimate HEC-HMS for more accuracy assessment rather than favism with on mode-1. Climate datasets of various model with RCPs scenarios predict streamflow with accuracy percent set for model. Bias corrected MIROC-5 precipitation climate datasets from 2011-2100 in mean three decades interval used for individual control points on downstream state.

MIROC-5 Climate Trend Analysis:

GCM Model for Interdisciplinary Research on Climate (MIROC-5) version predict best result in downstream state comparison discussed above, indices are generated from 3 decade mean rainfall to from 2011-2040, 2041-2070 and 2071-2099 for 4 RCPs. Mean cumulative annual decrement for RCP 2.6 & RCP 4.5 is -113.1mm and -161mm, while RCP 6.0 & RCP 8.5 indicate increment of 118.3mm and 156.1mm. Mean seasonal change in rainfall for Rabi season and Kharif season in RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 is 2.3mm, 2.24, 2.12, 2.21 and 2.93, 2.73, 4.38, 4.49 per day respectively. MIROC-5 rainfall is near to APHRODITE data in for all four RCPs in Rabi season and near to TRMM for RCP 2.6 & RCP 4.5 in Kharif season while higher for RCP 6.0 and RCP 8.5. Three decade interval from 2011-2040 annually cumulate indicate min decrease of -5.7mm for RCP 8.5, max decrease of -186.3mm in 2071-2099 while max increase for RCP 8.5 of 338.3mm and min increase for RCP 8.5 of 135.7mm in 2041-2070. Century RCPs scenarios predict rainfalls on the Chenab basin in seasonal shift from Rabi to Kharif increment for Kharif season 22%, 18%, 52% and 51% in RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5.

HEC-HMS predict equitant percent streamflow in comparison of percent shift from design discharge towards Kharif or Rabi season and on annual basis. Kharif season in Chenab River streams from equitant percent to Rabi season decrement due to climate change phenomena consideration of ocean and atmosphere in MIROC-5. Current century rainfall decrease and increase for RCP2.6 & RCP 4.5 and RCP 6.0 & RCP 8.5 is scenario of temperature consequently decrease and increase in streamflow for all three control points on annual basis from equitant streamflow.

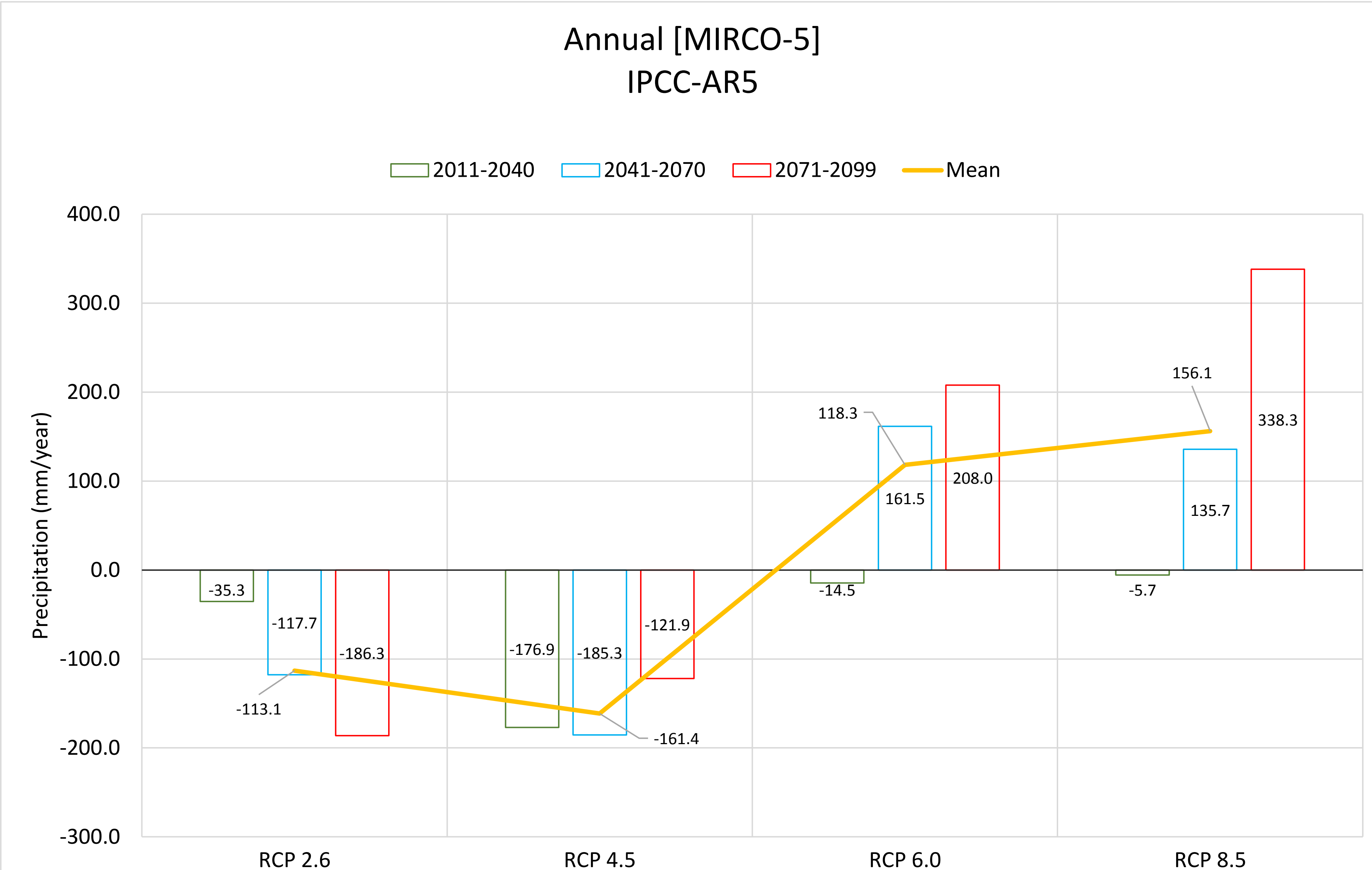


Figure 34: Annual MIROC-5 Rainfall

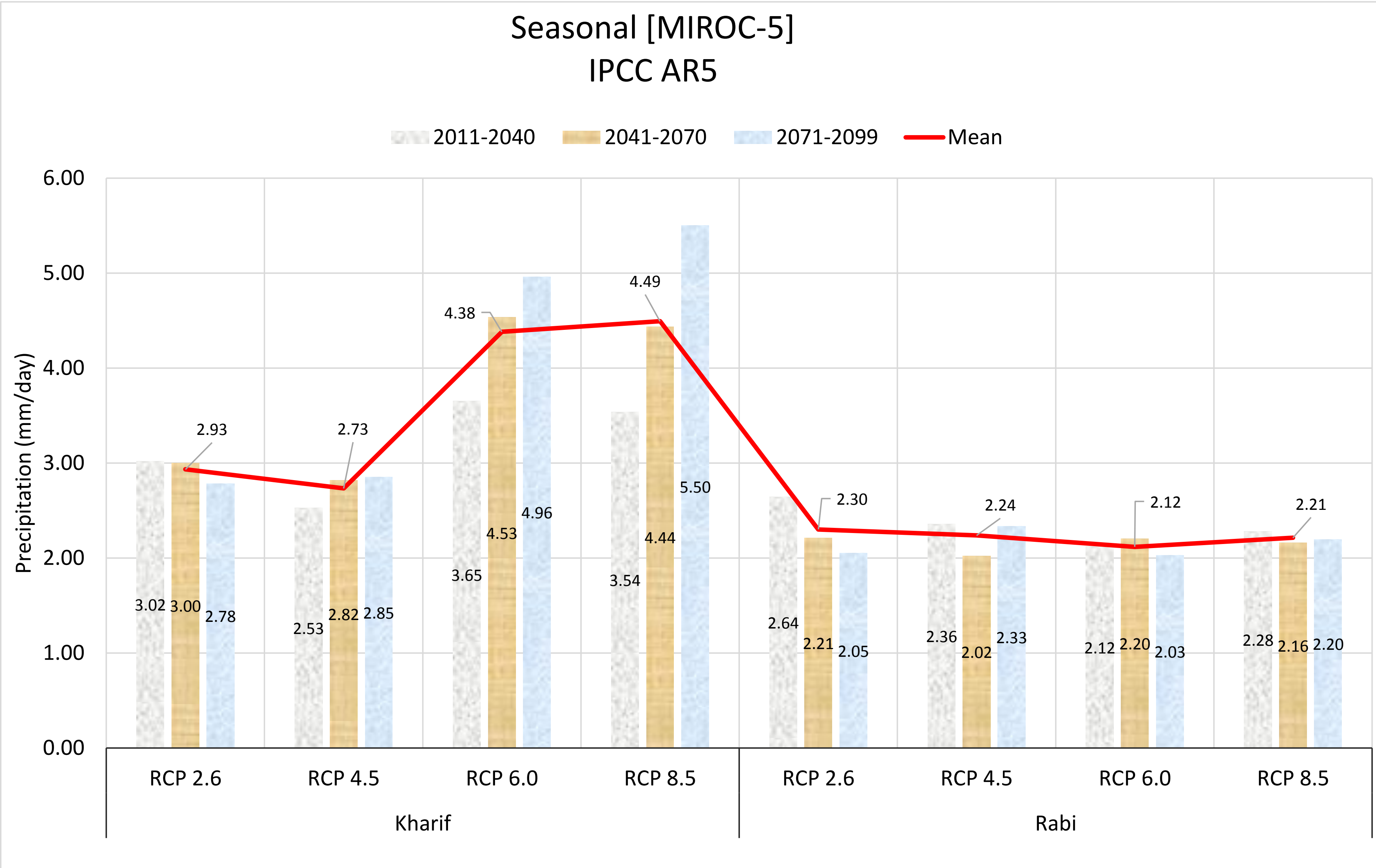


Figure 35: MIROC-5 Seasonal Rainfall

Annual Streamflow Change:

Annual equitant (Design Discharge) streamflow of three control points with shifting of RCP scenarios for MIROC-5 predict percent change in HEC-HMS streamflow for three time span of this century, 2011-2040 as '3D1', 2041-2070 as '3D2' and 2071-2099 as '3D3'.

$$Equitant\ Percent\ = 100 - [\frac{(Design\ Discharge - RCP)}{(Design\ Discharge)}\ x\ 100]$$

Marala Headworks mean streamflow for RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 is 59, 56, 74 and 76 percent equitant, Change in decades of 3D1, 3D2, 3D3 are in minimum and maximum of RCPs from mean as (max 5, 0, min 5), (min 1, min 2, max 3), (min 8, max 3, max 6) and (min 10, min 1, max 12) respectively with 74% HEC-HMS prediction. For Khanki Headworks mean streamflow for RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 is 92, 87, 116 and 119 percent equitant, Change in decades of 3D1, 3D2, 3D3 are in minimum and maximum of RCPs from mean as (max 8, 0, min 7), (min 1, min 2, max 5), (min 14, max 4, max 9) and (min 16, min 2, max 18) respectively with 81% HEC-HMS prediction. For Qadirabad Barrage mean streamflow for RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 is 78, 74, 98 and 101 percent equitant, Change in decades of 3D1, 3D2, 3D3 are in minimum and maximum of RCPs from mean as (max 7, 0, min 6), (min 1, min 2, max 4), (min 11, max 4, max 8) and (min 13, min 1, max 15) respectively with 74% HEC-HMS prediction.

Mean of all four RCPs of 3D1, 3D2, 3D3 in Marala Headworks, Khanki Headworks and Qadirabad Barrage as 66, 104 and 88 equitant percent with minimum and maximum change of (5, 6), (7, 9) and (6, 8) with 76% HEC-HMS prediction. Minimum from mean values are greater in numeric while maximum from mean values are less, RCP 2.6 from 2041-2070 indicate no change from mean values.

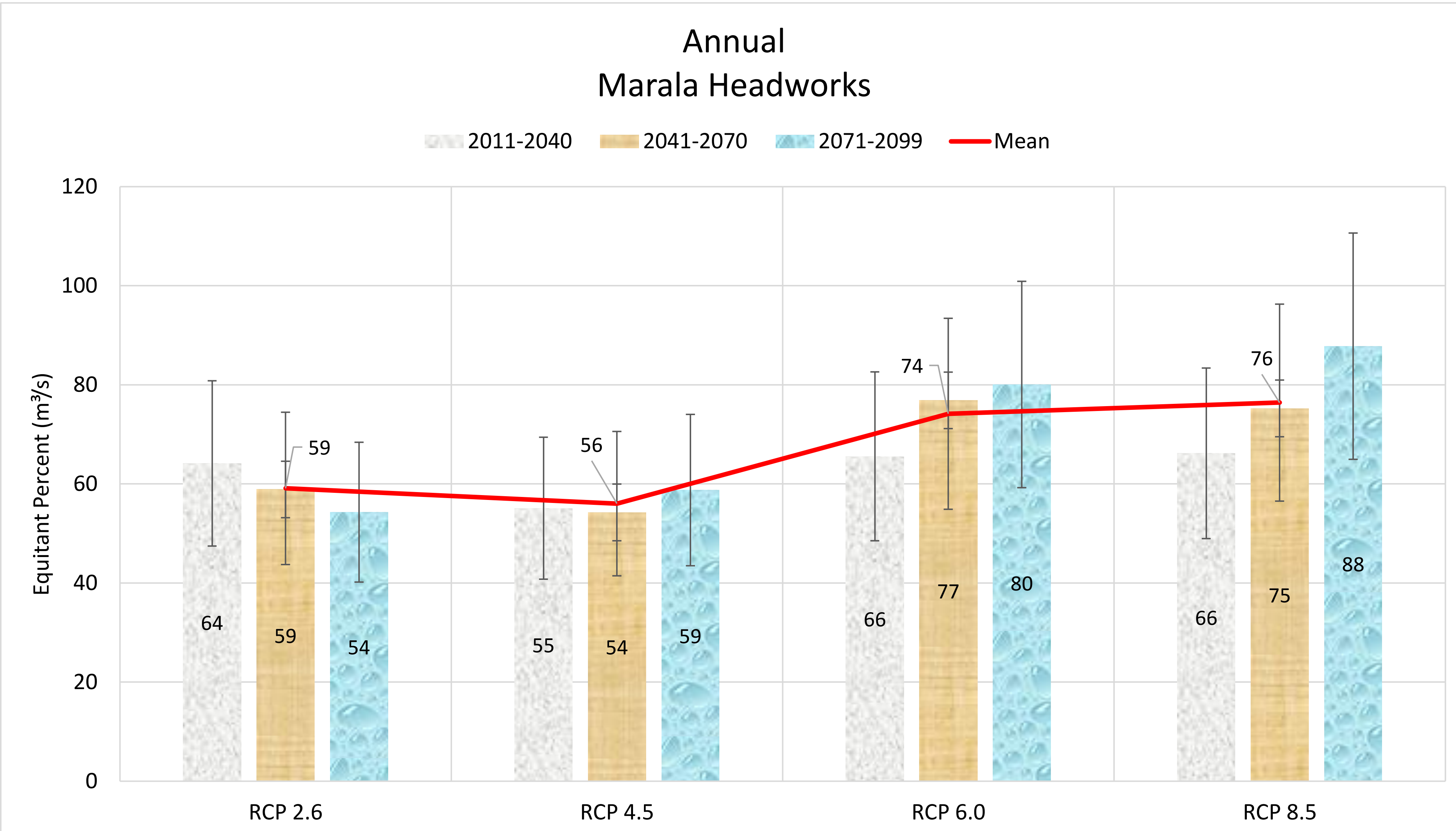


Figure 36: Equitant Annual Indices (Marala Headworks)

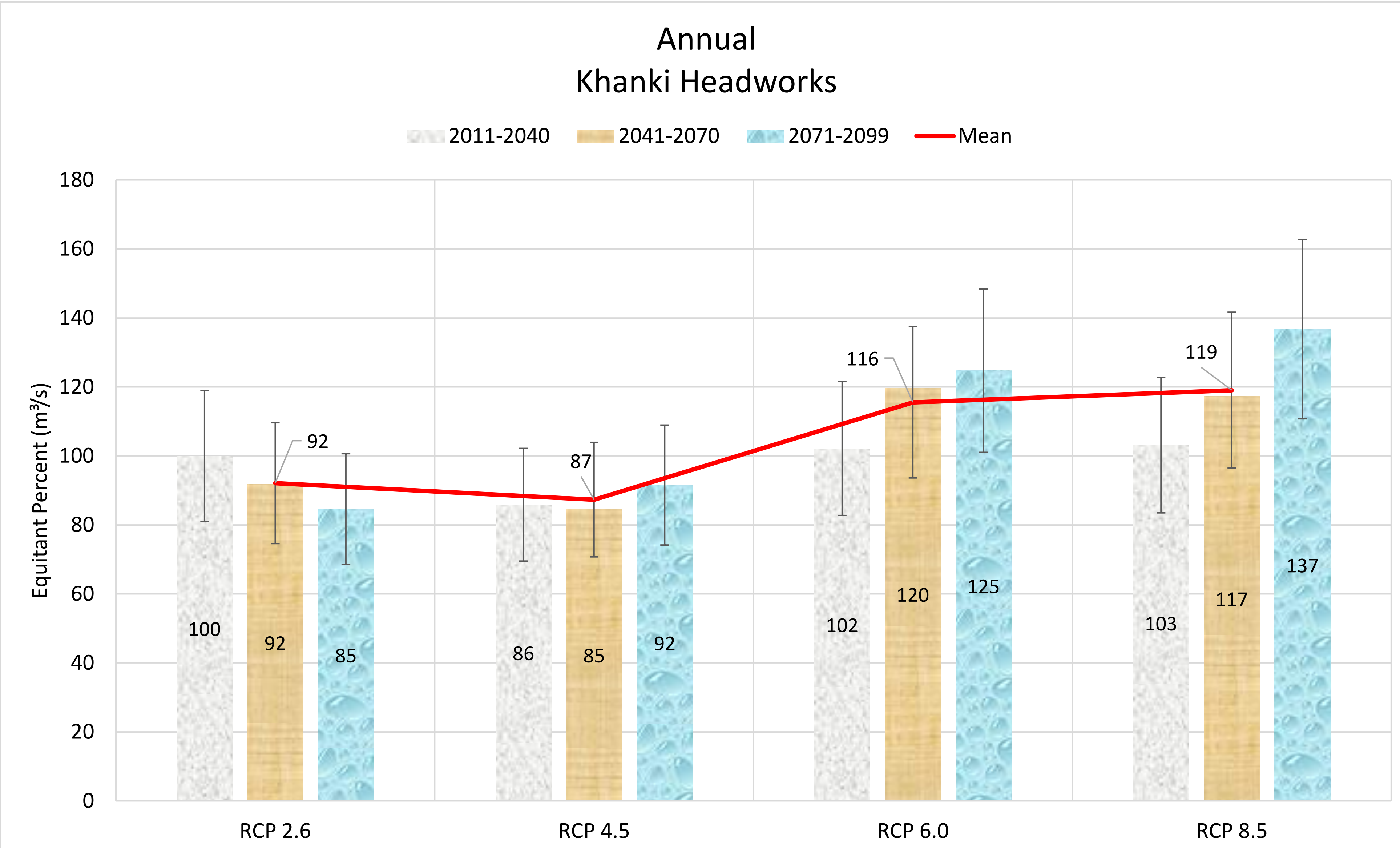


Figure 37: Equitant Annual Indices (Khanki Headworks)

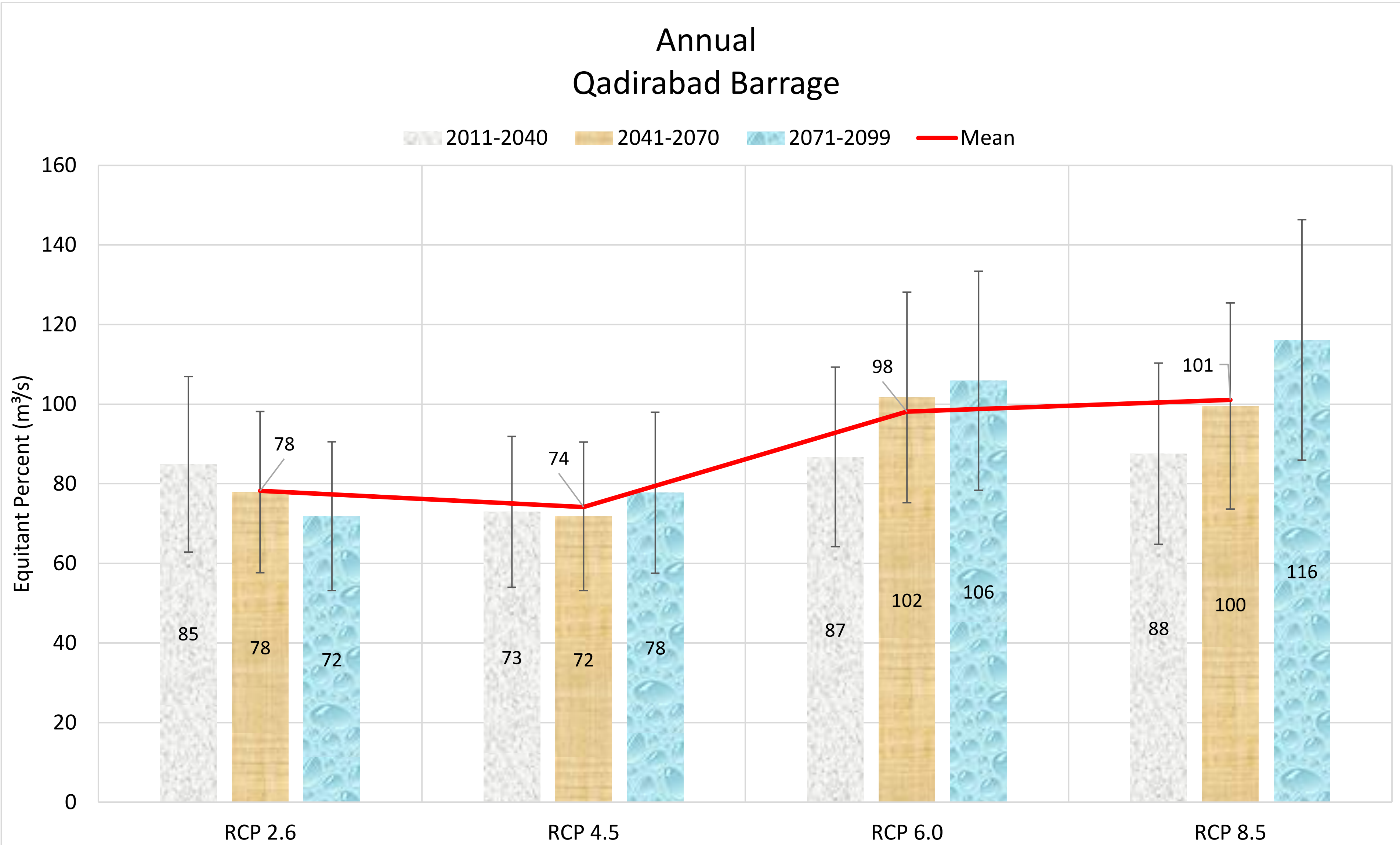


Figure 38: Equitant Annual Indices (Qadirabad Barrage)

Seasonal Streamflow Change:

Streamflow changes from Kharif towards Rabi season decrement due to high values of rainfall in RCP 6.0 and RCP 8.5, Kharif season is more accurate than Rabi season due to Influence of upstream state control points similarly as on annual comparison.

For Marala Headworks mean Kharif season for three time spans of 3D1, 3D2 and 3D3 equitant percent is 82, 80 and 87 for all four RCPs, similarly in Rabi season is 49, 45 and 45. In Kharif season change from mean is unique for RCP 2.6 & RCP 4.5 in decrease form and for RCP 6.0 & RCP 8.5 is increase form as (70, 59) and (85, 114) in 3D1, (69, 65) and (105,81) in 3D2, (64, 66) and (114, 102) in 3D3 respectively with 78% HEC-HMS prediction, In Rabi season change from mean is non-uniform (RCP 6.0-min 5, RCP 8.5-min 1), (RCP 4.5-0, RCP 2.6-max 7), (RCP 4.5-min 3, RCP8.5-0), (RCP 2.6-max 2, RCP 6.0-max 1) and (RCP 2.6-min 3, RCP 6.0-min 2), (RCP 8.5-0, RCP 4.5-max 4) respectively with 11% HEC-HMS prediction.

For Khanki Headworks mean Kharif season for three time spans of 3D1, 3D2 and 3D3 equitant percent is 114, 132 and 144 for all four RCPs, similarly in Rabi season is 77, 70 and 69. In Kharif season change from mean is unique for RCP 2.6 & RCP 4.5 in decrease form and for RCP 6.0 & RCP 8.5 is increase form as (109, 91) and (132, 126) in 3D1, (107, 101) and (163, 159) in 3D2, (100, 103) and (177, 197) in 3D3 respectively with 80% HEC-HMS prediction, In Rabi season change from mean is non-uniform (RCP 6.0-min 11, RCP 8.5-min 2), (RCP 4.5-0, RCP 2.6-max 10), (RCP 4.5-min 5, RCP8.5-0), (RCP 2.6-max 3, RCP 6.0-max 1) and (RCP 2.6-min 4, RCP 6.0-min 3), (RCP 8.5-max 1, RCP 4.5-max 7) respectively with 16% HEC-HMS prediction.

For Qadirabad Barrage mean Kharif season for three time spans of 3D1, 3D2 and 3D3 equitant percent is 110, 127 and 138 for all four RCPs, similarly in Rabi season is 73, 67 and 67. In Kharif season change from mean is unique for RCP 2.6 & RCP 4.5 in decrease form and for RCP 6.0 & RCP 8.5 is increase form as (104, 87) and (126, 121) in 3D1, (102, 96) and (156,152) in 3D2, (96, 98) and (170, 189) in 3D3 respectively with 71% HEC-HMS prediction, In Rabi season change from mean is non-uniform (RCP 6.0-min 8, RCP 8.5-min 1), (RCP 4.5-max 1, RCP 2.6-max 10), (RCP 4.5-min 5, RCP8.5-0), (RCP 2.6-max 3, RCP 6.0-max 1) and (RCP 2.6-min 4, RCP 6.0-min 4), (RCP 8.5-0, RCP 4.5-max 6) respectively with 18% HEC-HMS prediction.

Mean of all four RCPs of 3D1, 3D2, 3D3 for Kharif season in Marala Headworks, Khanki Headworks and Qadirabad Barrage as 83, 130 and 125 equitant percent with minimum and maximum change of (15, 17), (29, 29) and (28, 27) with 76% HEC-HMS prediction, For Rabi season in Marala Headworks, Khanki Headworks and Qadirabad Barrage as 46, 72 and 69 equitant percent with minimum and maximum change of (2, 2), (4, 4) and (4, 4) with 14% HEC-HMS prediction.

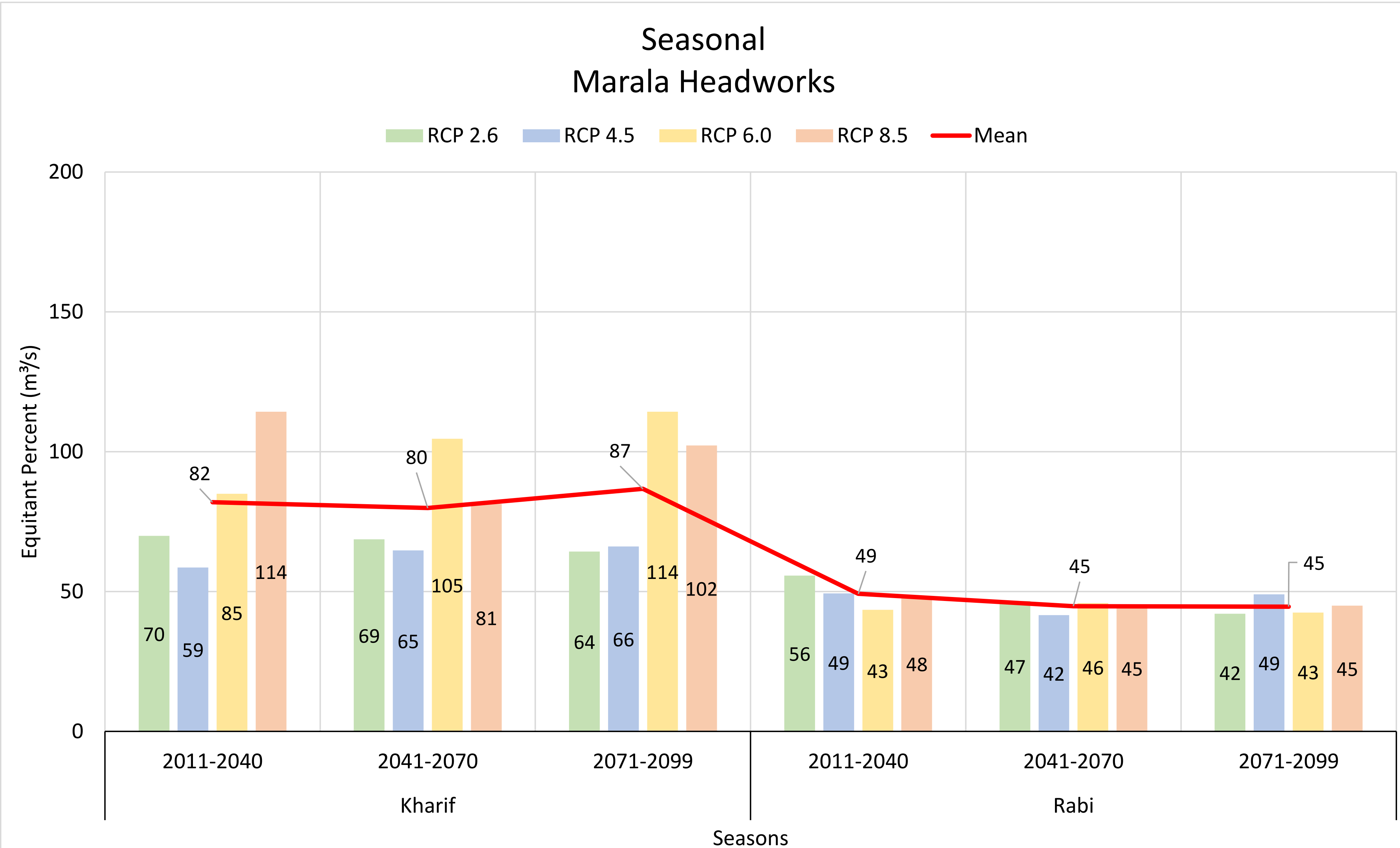


Figure 39: Equitant Seasonal Indices (Marala Headworks)

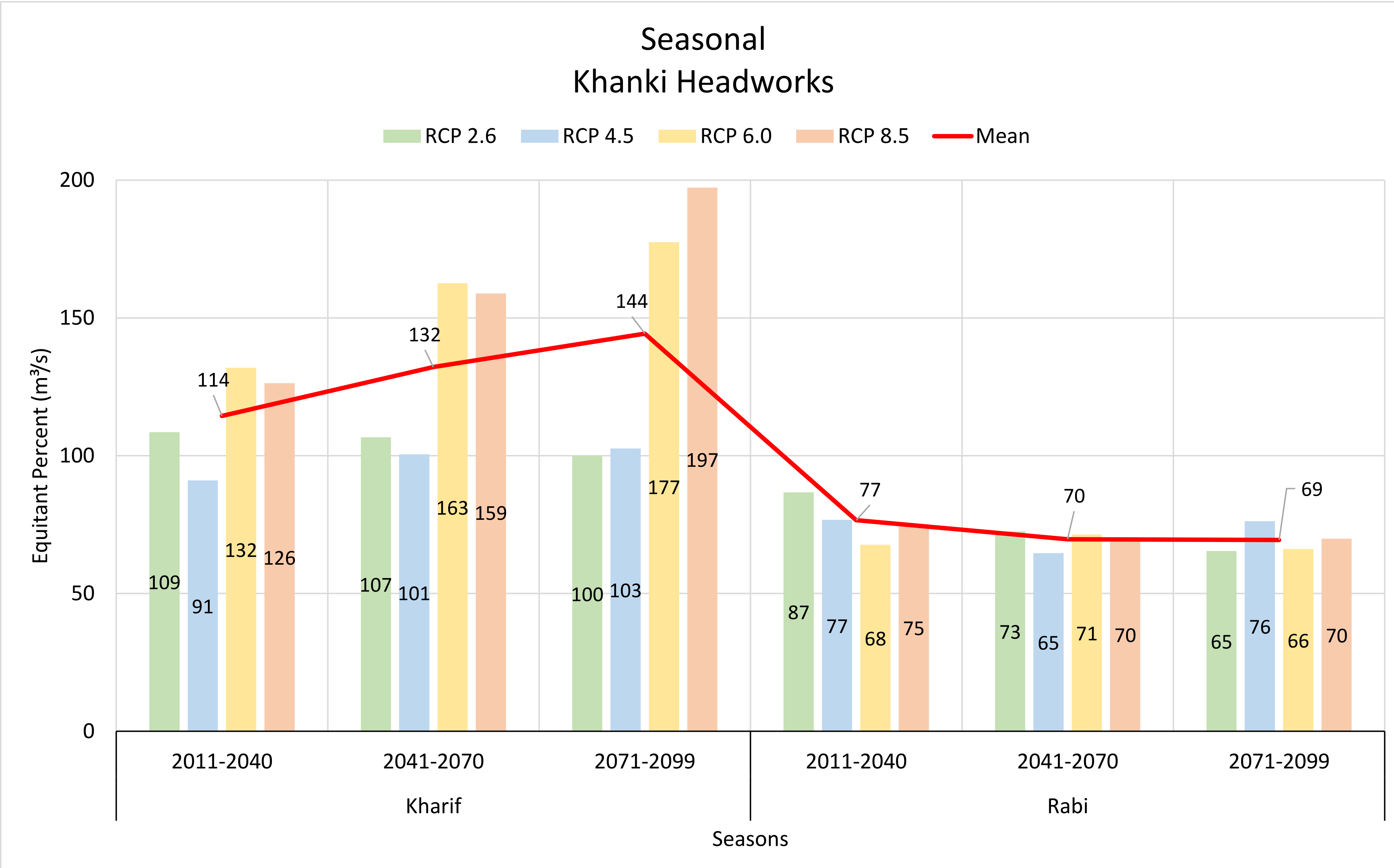


Figure 40: Equitant Seasonal Indices (Khanki Headworks)

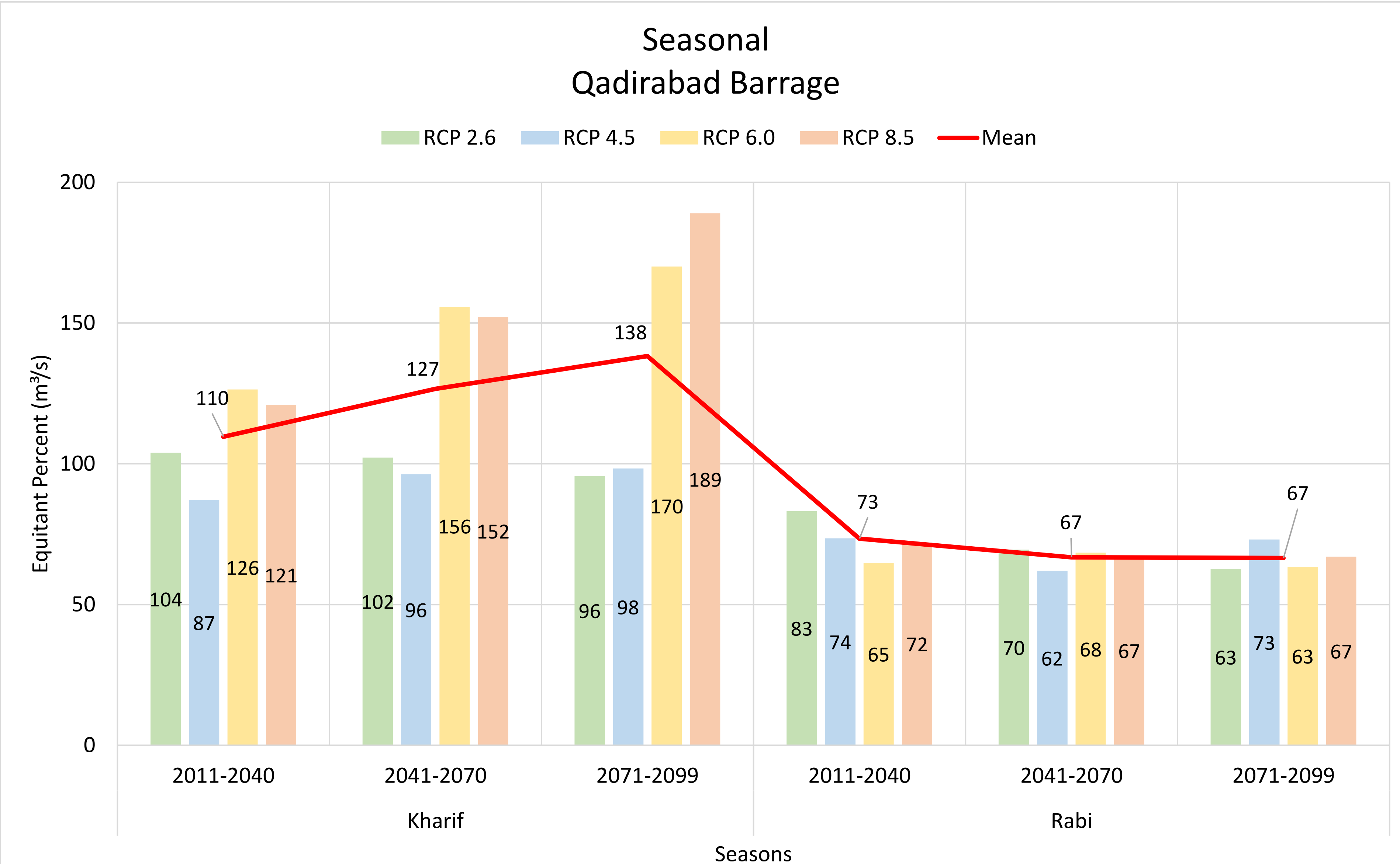


Figure 41: Equitant Seasonal Indices (Qadirabad Barrage)

Chapter 5
Conclusion & Recommendation

Conclusions:

Continuous projection and prediction on annual and seasonal basis for hydro-meteorological datasets of TRMM & APHRODITE in equal spatial and temporal resolution project maximum accuracy of streamflow in Chenab basin for estimation of future climate based streamflow, TRMM is more accurate in term of HEC-HMS projection on annual basis due to it greater time accumulation for 24 hours, while APHRODITE is not as accurate, maximum accuracy of 81% achieve for TRMM while 68% for APHRODITE in mode-1. In term of favism in less or more phase TRMM is less favorite while APHRODITE is more favorite, on seasonal basis maximum accuracy of 80% is achieve in Kharif season while Rabi season is 18% accurate for streamflow of TRMM projected dataset in lumped format with pseudo-distribute approach in downstream state of Pakistan.

Climate dataset prediction of MIROC-5 in HEC-HMS with no comparison, RCPs formulate streamflow with maximum accuracy and less favism which indicate high sensitivity of model for change due to no parameter shift expect for Rabi season. On annual basis at downstream state Marala Headworks streamflow per day reduce on mean value of 265 cumec, while Khanki Headworks & Qadirabad Barrage increase on mean value of 231 & 64 cumec for current century from design discharge. On seasonal basis of Kharif and Rabi, Marala Headworks, Khanki Headworks and Qadirabad Barrage Kharif season predict mean 13, 529 and 520 cumec increase in streamflow per day while Rabi season reduce streamflow on mean 39 cumec, increase 806 and 611 cumec per day for above mentioned control points.

Marala Headworks decrease streamflow while increase in all scenarios of annual and seasonal basis for two downstream control points of Khanki Headworks and Qadirabad Barrage conclude no additional inflows required, first control point shift streams downstream to regulate outflows from up-tropic river basin estimate 2.94 cumec on annual addition.

Recommendations:

Chenab basin is mismanages with less and more discharge at three control points of downstream state which recommend additional channel of above mentioned streamflow while two controls point indicate updating of FDC (Flow Duration Curves).

Limitation of this research; Mode-2 of Chenab basin in reverse modeling is yet to project on flood prone time span and predict streamflow on downstream state, secondly slope of Mangla-Marala Link Canal (MMLC) of additional streamflow's slope is not calculated due to non-consideration of Jhelum basin, only MIROC-5 Model used for prediction of streamflow in HEC-HMS due to second rank in Pakistan more Asian developed GCM of CORDEX (Coordinated Regional Climate Downscaling Experiment) can be used with comparison. Trimmu Barrage excluded from research work due to confluence with Jhelum River upstream. More addition to this lumped format Chenab can predict streamflow with fully distributed model.

Peak streamflow is manage with ASR (Aquifer Storage & Recovery) with wells level information and interpolate with Inverse Distance Weighting (IDW) to locate points to be implemented.

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