“Run of the River projects along Chenab River and Its impact on Seasonal flows in Pakistan at Marala”

By

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DEDICATION

Dedicated to my dearest family and friends

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First and foremost, I must acknowledge my limitless thanks to **Almighty Allah**, for his mercy, help, and blessings and for making me strong enough to go through thick and thin in Life.

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Romaisa Babar Abbasi

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LIST OF ABBREVIATIONS

MERRA-2	Modern-Era Retrospective analysis for Research and Applications, Version 2
TRMM	Tropical Rainfall Measuring Mission
NSIDC	National Snow and Ice Data Centre
SRM	Snowmelt Runoff Model
CC	Correlation Coefficient
RMSE	Root Mean square error
IWT	Indus Water Treaty

ABSTRACT

The role of river flow in maintaining ecological balance is well acknowledged and the river flow alterations in upper riparian zones have serious repercussion for lower riparian zones across the globe leading to trans-boundary water sharing issues. Under the umbrella of Indus water treaty (IWT) 1960, with the prime focus on Chenab catchment, current study examines the variability in inflows at Marala (1990-2020) under changing climate and increased development of Hydro power projects by India. This study tries to draw a linkage between climatic variables and variability in flows at Marala keeping in view the increased development of Runoff river project. The trend analysis of inflows have shown significant decrease in annual flows (i.e Sen's Slope = -0.057, Tau = -0.131with p-value less than 0.05). As per quantitative assessment, there is almost more than 38 % decrease in flows as compared to 1990's level. To assess the decreasing trends in flows, climatic variables were also explored and it was found that the precipitation (major contributing factor in runoff) data has not shown any significant negative trend in any season throughout the year which can explain decreasing flows at Marala. Moreover Snowmelt Contribution estimated for SRM were also explored to draw linkage between changes in flows and snow melt. For this purpose regression analysis was done. The results of regression have shown no significant correlation with any of climatic and hydrological parameter such as precipitation, temperature, Snow Cover area and Snow Melt Contribution. However, when annual flows were correlated using linear regression with storage capacity of dams existing in Chenab Basin, significant negative correlation was observed i.e. decreasing flows with increasing storage in the catchment.

Chapter 01

INTRODUCTION

1.1. Background Information

The anthropogenic river flow alterations in western rivers in Indian occupied Kashmir have serious repercussions for ecological regime of Pakistan located downstream. The role of river flow in maintaining ecological balance is well acknowledged. Therefore, several studies have been done since long. Doll et al. (2009) made an attempt to do a comprehensive analysis of flow alteration Globally. The study has found several areas around the world where rate of river flow alteration is higher. Among these areas Pakistan and India is also highlighted.

The formation of reservoir and dams has its own positive aspects such as power generation and maintaining fresh water supply. However, storage at high lands have concerns for Pakistan which need to be understood through a scientific approach and addressed thereon through policy dialogues. Biemans et al. (2011) believe that this may affect by altering river dynamics of water, nutrients and sediments, habitat fragmentation and less available water for sustaining agriculture at the lower riparian's end.

Apart from the possible ecological impacts, the cross-boundary river has political implications as well. It is a common belief in Pakistan that India by taking advantage of its geographical location has used best of its efforts to control the water of Pakistan. This dispute between Pakistan and India over sharing of trans-boundary water resource in Indus river basin led to Indus Water Treaty (IWT) (1960). Although IWT has allocated rights of both countries in eastern and western river but India has time and again took advantage of its geographical location and started constructing many dams on western rivers depriving Pakistan of its due right of water sharing. Increasing development on Chenab and Jhelum rivers exacerbated trans-boundary water conflicts. The increasing vulnerability of Pakistan to water scarcity has been examined thoroughly in existing literature (for example, Archer et al. 2010; Immerzeel, van Beek, and Bierkens 2010)

1.2. Indus Water Treaty

In 1947 after Indo-Pak independence, west and east Punjab were separated, and exiting states for example part of Kashmir was added to a transitional status, which led to the cut short of water of the Indus river basin and it further led to uncertainties regarding development in basin in India and Pakistan.

After many years, with the support of World Bank, rigorous negotiation led to "Indus Water Treaty" (IWT). The trans-boundary water issues have always been a part of India - Pakistan conflict. The IWT (1960) has given rights of three (3) eastern river to India and three (3) western rivers to Pakistan. Their glaciated basins rise in amazingly complex terrain of the Karakoram, Hindu Kush, western Himalayas in China, Pakistan and India.

It is generally expected in Pakistan that these rivers should carry their full natural flow, with limited uses in upstream under provision of Indus Water treaty. While at upstream India expects, that it has due right to construct run-of-river projects/hydropower facilities and uses allowed under the treaty. The balance among their hydrologic and social perspectives on water sharing and use vary.

Despite allocation of western rivers, Pakistan has failed to exercise its due rights on western river. The reason of this lies either faults in policy making of Pakistan or far better foresightedness of India. India has started construction of several projects on Chenab to harness maximum benefit leaving Pakistan in distress.

The IWT has undergone various conflicts over time, and due to upper basin development the new pressures arose. In 2007, for the first time a neutral expert (under the Indus water Treaty's article which provides for employing a "neutral expert" on issues unable to be resolved by both parties) was employed to resolve issue of “Baglhiar Dam” on the river Chenab. Contrary to point of Pakistan in water use and sharing issues India has always rejected the allegation of undue use water of western rivers. India has attributed the Pakistan’s views as a trust deficit and justified its power projects in line with right allocated to India by IWT (Bansal, 2005). Whereas, non-disclosure of details related Tulbul/Wullar project and later regarding Baghliar dam, Pakistan finds a good reason to doubt Indian intentions, when it comes to water sharing issue (Gazdar, 2005).

When Indus Development Project was completing in Pakistan during 1970’s and there was a hope for the supply of irrigation water in required amount, Salal Dam construction was started. India’s this action had jeopardized the water supply from Chenab.

It was followed by Wullar Barrage (on Jhelum), Baglihar dam and Kishanganga afterwards. The tension between two countries over Salal dam was resolved somewhat amicably. Whereas the dispute of Kishenganga and Wullar barrage remained far from settling. Similarly, the Baglihar dam issue was resolved through mechanism given in Indus water Treaty for resolution of Dispute. But in 2008, due to storage of water in Baglihar Dam negatively affected the flows downstream depriving the Pakistani Formers to have requisite water at sowing season (Zawahri,2009 &Akhtar, 2010).

A major conflict that the Indus water treaty identified but failed to fully address is that the upper riparian zone of all three western rivers lie in the disputed territories of Azad Kashmir (controlled by Pakistan) Janmu Kashmir (controlled by India) and Gilgit-Baltistan. The long-term internal water needs of these areas have been changing since the IWT was signed. Moreover, impact of changing climate on the hydrology of all rivers—i.e., droughts, floods, and shifts in the runoff timing give rise to serious concerns up and downstream.

With the passage of time India is increasing number of Runoff river projects in Chenab river basin. A number of small runoff-river projects across the Himalayan region are a serious concern to the hydrological regimes of rivers and “Himalayan biota”. According to the Himachal Pradesh Directorate of Energy, till December 2019, nearly 965 identified runoff river projects for hydro power generation in Hemchal Pardesh with a capacity of 27,436 Mega Watts. 216 of the 965 identified plants (including projects with a capacity of less than 5 MW) had been commissioned and were operating. Only 58 of the known projects (with capacity of more than 2300 MW) are under construction. Almost 640 projects (with an installed capacity of nearly 9260 MW) are in stage of clearance . Moreover, 30 projects (with capacity of 1304 MW) are waiting for allocation. And only four projects (with capacity of 50.50 MW) are disputed or cancelled (Sahu, et. Al. 2020).

In the light of facts referred above, it is very important to dig deeper into the matter on individual basin level. Therefore, the current study focuses on assessment of reduced flows at Marala as result of increased number of reservoirs made by India and resultant impact on flows.

Objective:

The current study aims to understand the contribution of run-of-the-river projects along with precipitation in the discharge of Chenab River Basin in the context of changing geo-political and natural climate.

Chapter 2

LITERATURE REVIEW

Mirza (2008) for the first time introduced Kashmir issue from a new perspective. In his study, it is highlighted that how Kashmir issue is much more of a resource war to control Indus water resource than an ideological war. This study comprehensively discussed all major events in Indo-Pak hydro-politics starting from the very first issue after IWT.

Arora, et al. (2008) studied the sensitivity of snow melt in Chenab River basin Using SNOWMOD model. The study indicates that the snow melt is somewhat more sensitive to changes in temperature then to summer precipitation. Bhutiyani, et. Al. (2008) studied the long term variation in river flows in western Himalayas. The study made use of Mann Kendal Trent test and linear Regression. The results of study indicated that in Chenab river basin (between 1969 to 1998) decreasing trend in flows was observed in spring season only while all other season indicated increasing trend. It is worth mentioning that this study included the part of Chenab River Basin located in Indian Territory.

Investigation on the impact of hydropower projects (such as dams etc) on the hydrology of river and its environment around, is important in management of river basin. Nevertheless, due to its complexity it has become a difficult scientific issue. Zhang et. Al., (2010) have studied changing flood regimes in Huai river basin in China in perspective of increasing dam construction in basin. The result of study indicated that in dry years the river flows were decreased upto 12 % in the river basin.

Akhtar (2010) have argued while analyzing various aspects of Indus water dispute that apart from fighting shortage of water, the increasing number of reservoirs allow India to control flows of Pakistan. It is further added that taking advantage of high riparian zone India can release in wet season leading to flood situation in the areas downstream and can store water in dry season and. The same has been highlighted by others. Qureshi (2011) have also highlighted the fact of decreasing flows in Pakistan due series of dam construction on western rivers. The study has also highlighted the challenges faced by country due to improper management of available reservoirs and no development of new reservoirs.

Jamir (2016) have highlighted the Kashmir Valley flooding in 2014 because of increasing reservoir construction on Jhelum and Chenab. It is further indicated that increase risk of flooding as these projects involve heavy construction, river diversion, deforestation and huge amount of debris from each project. This study attempts to ascertain role of Indus Water Treaty on water sharing issues.

As per Adnan, (2018) Pakistan has justified reservation against Salal hydro Project, Baglihar Dam (450 MW) and Ratle Dam (850 MW power project) on Chenab river. Ratle dam is believed to have reduce 40% of flows at Marala head. Similarly, Wullar Barrage Project also known as Tulbul Irrigation Project on Jhelum River (started in 1984), along with Kishanganga dam (a 330 MW power project) is hampering river flows in downstream. Pakistan’s Neelum Jhelum power project of 900 MW capacity is located down stream of Kishanganga, which is also at risk due to Kishanganga.

As far as quantitative assessment of river flows is concerned, studies have shown increasing flows in spring and winter season and decreasing in summer and autumn (Khattak et al., 2011; Ahmed et al., 2018 & Dimri et al, 2018). All these studies have used Mann Kendall trend analysis to draw seasonal trends. Whereas the variations in flow are not analyzed from the perspective of increased storage reservoir on the rivers in upstream. Therefore, the current study is aimed at analyzing flow variations quantitatively in relation to increasing construction of reservoirs and hydel power projects.

Investigations carried out by Kour and Jasrotia (2012) indicated an increase in discharge conditions in 2020s and decrease in discharge in long run. The study used Hydrologiska Byrans Vattenbalansavdelning (HBV) model.

Another study carried out by Shakeel & Iqbal (2016) focusing on trans-boundary impact of Indian hydropower projects, keeping in view the aspects of quality, quantity and temporal change in river course. Results indicated that the increasing dam construction with in Chenab River Basin, a downward trend and significant variability in river flow was seen with an average decrease of 0.5 x $10^8 m^3$/year in annual inflows.

Several studies have been done to estimate snow melt contribution in snow covered basin. Azmat et. Al. 2018 & 2020 have tried to assessed different hydrological models' performance in Jehlum and Hunza River basin. These study concluded that SRM proves to be good in estimation of runoff where snow melt is contributing in flows. Therefore this study has used SRM to estimate snow melt Contribution.

A study conducted by Grover, et. Al. (2022) in Chenab river basin shows that precipitation is decreasing in near future and temperature increases in this century. Modeled river flow is expected to show upward trend in the 21st century. The study have used HBV model for runoff simulation.

Chapter 03

MATERIALS AND METHODS

3.1. Study Area

The study is regarding Chenab Basin, which along with Jehlum, is one of the important rivers of Indus basin. The Chenab and Jhelum rivers are tributaries from the western Himalayan region of Indus catchment, with a total area of about 50,000 square Kilometers, and both of these basins have combined area of almost 220,000 square Kilometers and contribute an approximately 110 Million Acre Feet of the annual flow of the Indus River. Out of the total 110 MAF, 22 MAF is from Chenab River.

The Chenab basin is located between 30- 34° North and 74- 78°East covering an area of around 27000 Km^2 (Jain et al. 2007), 10 percent of the total basin area is glacieted (Figure 1). The basin elevation is between >300 meters to <7,700 m. Ice and snow make an important part of hydrology of Chenab catchment. Akhnoor is the end point of the basin located in Indian Territory before it enters into Pakistan. It is estimated that nearly thousand small and large glaciers feed the Chenab River (Grover et al. 2020). The upper part of catchment is located between the middle Himalayan range (Pir Panjal and Zanska), which is categorized by availability of many glaciers and precipitation at a slower rate during winter season . The lower part of Chenab catchment is located within the lower Himalayan range and characterized by high amount of precipitation and winters are shorter (Grover et al. 2020). Because of variability in altitude, lower reaches of basin and valleys have tropical & moist climate, and at an elevation of 1,500–2,000 m temperature is lower and gradually gets colder at elevations further above.

The Chenab catchment has very high hydropower generation capacity as compared to other basins, with an estimated capacity around 11000 Mega Watts (Sharma & Thakur 2017). Due to climatic changes, temperature increase and changing precipitation pattern are likely to be seen in future which will affect the hydrological regime of this basin. This raises concerns regarding maintenance of the flows in the river, which resultantly will affect the hydropower projects located in the basin.

The Chenab river makes its way through the Jammu Kashmir and finally enters in Pakistan at Marala. The river further descends to meet Indus at Mithankot. The length of river is 960 Km approximately, of which 274 Km is in Pakistan. with 41,656 square kilometers of catchment area (Mahmood & Rani, 2018). The Chenab basin has a surface area more than 22,000 square Kilometers and a glaciated area of 2,700 square kilometers. As Chenab is located in western Himalayas, thus the winter snow is amplified by the monsoon precipitation in summer season in the Chenab and by a small glacial melt component. The map of study area is shown in **Figure 1.**

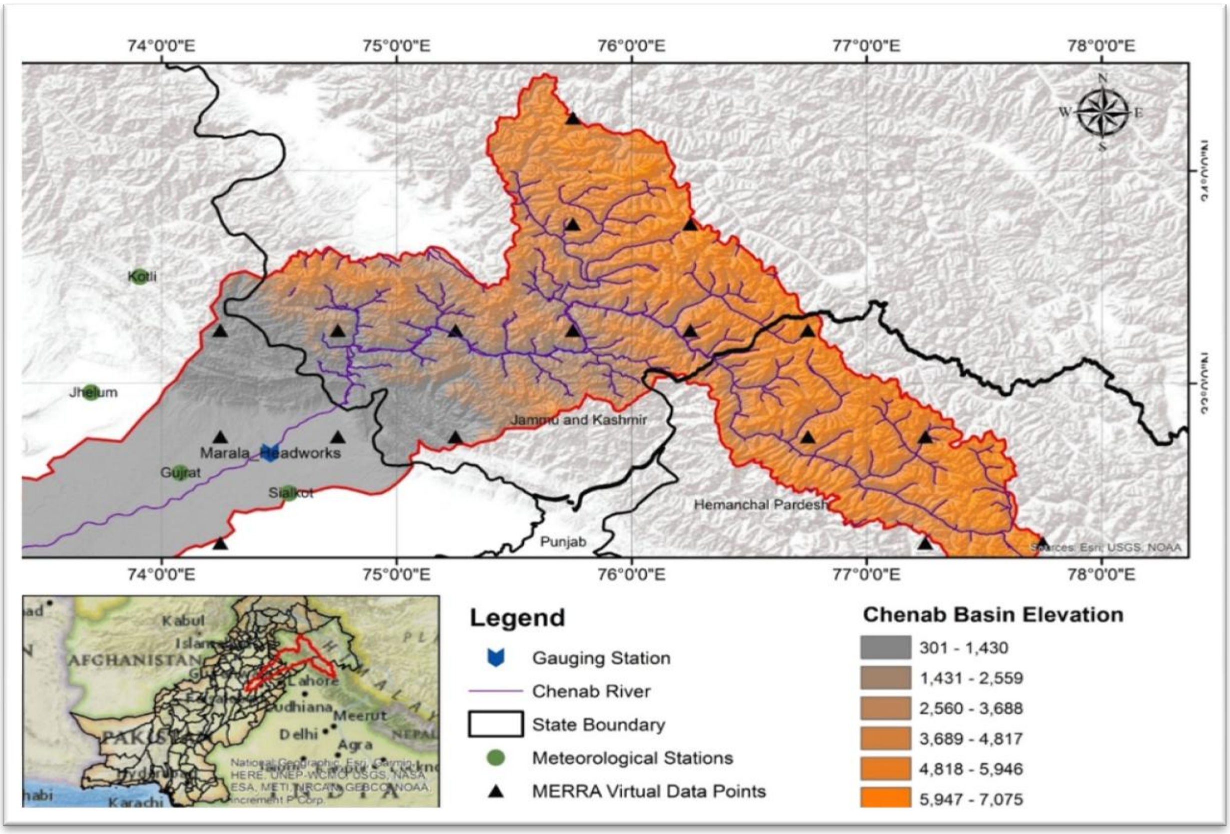


Figure 1: Study area map, showing Chenab Catchment along with location of MERRA-2 virtual data points and PMD Stations for meteorological data used in study.

3.2. **Methodology**

3.2.1 **Datasets**

The study made use of precipitation and temperature data acquired from Pakistan Meteorological Department for the period of 1990-2020. However, there was only one station of PMD, which is located in Chenab catchment. Therefore gridded data sets were also explored to assess the precipitation and temperature of trans-boundary Chenab River catchment.

For this purpose, two data sets i.e. “Modern-Era Retrospective analysis for Research and Applications, Version 2” (MERRA-2) & “TRMM (TMPA) Precipitation L3 1 day 0.25 degree x 0.25 degree V7”, were used. Both data sets were validated with ground stations available within the catchment and nearest to catchment. 17 virtual data points were extracted from best fitted dataset. Out of these 17 virtual points 11 virtual points within the upper Chenab catchment were used for trend analysis.

Data of daily inflows at Marala was acquired from XEN irrigation Marala for period 1990-2020. The study also used Snow cover data for the purpose of assessment of contribution of snow melt in runoff at Marala. The snow cover data was used for simulation of Snow Melt runoff through Hydrological model named as SRM. The Snow cover data was acquired from National Snow and Ice Data Center (NSIDC) for period of 1990-2020. The data used was “Rutgers Northern Hemisphere 24 km Weekly Snow Cover Extent”. SRTM Digital elevation model was also acquired for Chenab River catchment for basin delineation and making elevation zones.

The datasets used in the present study are given in Table 1 which is as follows.

Table 1: Detail of datasets and processing

<table>
<tr><th>Feature</th><th>Specification</th><th>Sources</th></tr>
<tr><td>Precipitation Data (Meteorological Stations and Gridded Data sets for ungauged part of catchment)</td><td>➢ Latitude and longitude of the weather station
➢ Rainfall (mm)
➢ TRMM Product Precipitation (TRMM_3B42_Daily_7) (0.25*0.25)
➢ MERRA-2 Precipitation Product (0.5*0.5)</td><td>Pakistan Meteorological department (PMD)
NASA</td></tr>
<tr><td>River Flow data</td><td>Gauging station located in Catchment (MAF)</td><td>Irrigation Department</td></tr>
<tr><td>Elevation Data</td><td>SRTM DEM (30 m)</td><td>USGS</td></tr>
<tr><td>Data regarding Existing and planned projects at Chenab</td><td>Location
Name</td><td>Published Maps
Project Feasibility Studies.</td></tr>
<tr><td>Snow Cover data</td><td>“Rutgers Northern Hemisphere 24 km Weekly Snow Cover Extent, September 1980 Onward, Version 1 (G10035)”</td><td>National Snow and Ice Data Center (NSIDC)</td></tr>
<tr><td colspan="3">Tools (Software)</td></tr>
<tr><td colspan="2">Microsoft Excel, R Studio</td><td>ArcGIS</td></tr>
</table>

3.2.2 Analysis of existing projects in Chenab catchment and variations in Flows at Marala

For mapping the existing projects in the catchment published literature and reports were consulted and spatial mapping of existing and planned project was done.

3.2.2.1. **Trend Analysis**

For analyzing trends of inflows at Marala the Man Kendall Trend test was used, which is widely being used to assess the changes in climatic variable. Moreover, World Meteorological Organization, has also recommended Man Kendall test for meteorological trend studies (WMO, 1988 and Mann, 1945).

For examination of trend in climatological and hydrologic time series data, the MK test is frequently utilized (Khaled 2008). The non-parametric nature of the test means that it is not dependent on regularly distributed data. Additionally, because the test is less susceptible to sudden breakdowns, it can even be used for inhomogeneous time series data. The alternative hypothesis (H^1), which presupposes that there is a pattern in the data, is evaluated against the null hypothesis (H^0), which states that there is no trend in the given time series (the data are independent and randomly arranged).

The test statistic Zs is estimated to determine the significance of the trend for n>=10 and is nearly normally distributed. The result is deemed to be significant with the presence of a trend in the data if p-value is less than the given significance level (alpha) = 0.05 and H^0 is rejected otherwise H^o is accepted for p=>0.05

Sen's slope was applied to better evaluate the trend's size. Sen's slope is a non-parametric technique that isn't impacted by outliers and glaring data errors. Median of all the slopes measured between all the subsequent data points time series is used to get the Sen's slope (β).

The equation used for Man Kendall statistics is given below;

S= $\sum_{i=2}^{n} \sum_{j=1}^{i-1} Sine(xi - xj)$ (1)

3.2.3 Evaluation of Datasets

Validation of data sets was done by comparing the data of ground stations (given in figure 1) with the values of the grid with in which PMD's meteorological station falls. The point values of Centroid of each grid (NetCDF file) were extracted using ARC GIS Model maker. Then both datasets TRMM & MERR2 were evaluated using RMSE and Correlation Test. For analyzing trends of inflows at Marala the Man Kendall Trend test was used.

(i) **Root Mean Square Error (RMSE)** usually summarizes the difference between observed and estimated values (Wellmont, 1982). Therefore it is to be used to assess the performance of gridded data sets and can be calculated by following equation;

RMSE= $\sqrt{1/N \sum_{i=1}^{N} (Xgrid,i - Xobs,i)^2}$; (2)

where Xobs is observed values and Xgrid is gridded value.

(ii) **Correlation Coefficient** are another measure, which calculated degree of association between two variables, there are different correlation test are available. They are either parametric or non-parametric. The parametric test is recommended when data is distributed normally while nonparametric test is used when data does not follow normal distribution. In certain cases when distribution is not known **t** test or Kendall's rank correlation, a non-parametric test is used (Mann, 1945) and can be calculated by following equation.

$\tau = 1 - 4Q/n(n=1)$ (3)

where Q refers to the number of inversions needed for y to obtain same order as x

3.2.4 Snow Melt Contribution

The SRTM Dem (30m) was used to delineate the catchment in ARC GIS software. Once the basin. Thereafter the snow cover dataset was processed using ARC GIS Model maker to extract weekly values of Snow cover. Zone-wise snow cover was also extracted using Zonal Statistic Tool (Extracted Zones and area is given in table 2). Once the snow cover data was extracted, linear interpolation was done to convert weekly data to daily data, which is prerequisite for SRM to run.

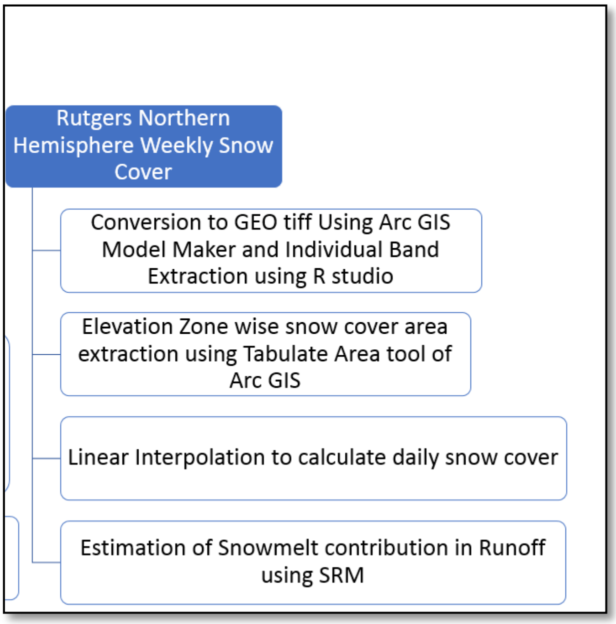


Figure 2: Flow chart diagram showing processing of NSDIC's Snow cover dataset.

Based on hypsometric calculations using Arc GIS, six (6) elevation zones were extracted and using tabulate area tool, zone wise area was calculated. Detail is given in Table 2.

Table 2: Hypsometry

Elevation	Zone	Mean Elevation	Area in Km^2	% Area
<1500	1	983.6482356	1883.665	7.093687
<2500	2	2033.744165	3605.692	13.57866
<3500	3	3024.614961	4659.522	17.54728
<4500	4	4035.871589	7334.424	27.62068
<5500	5	4963.421382	8121.491	30.5847
<7500	6	5685.239485	949.3081	3.574996

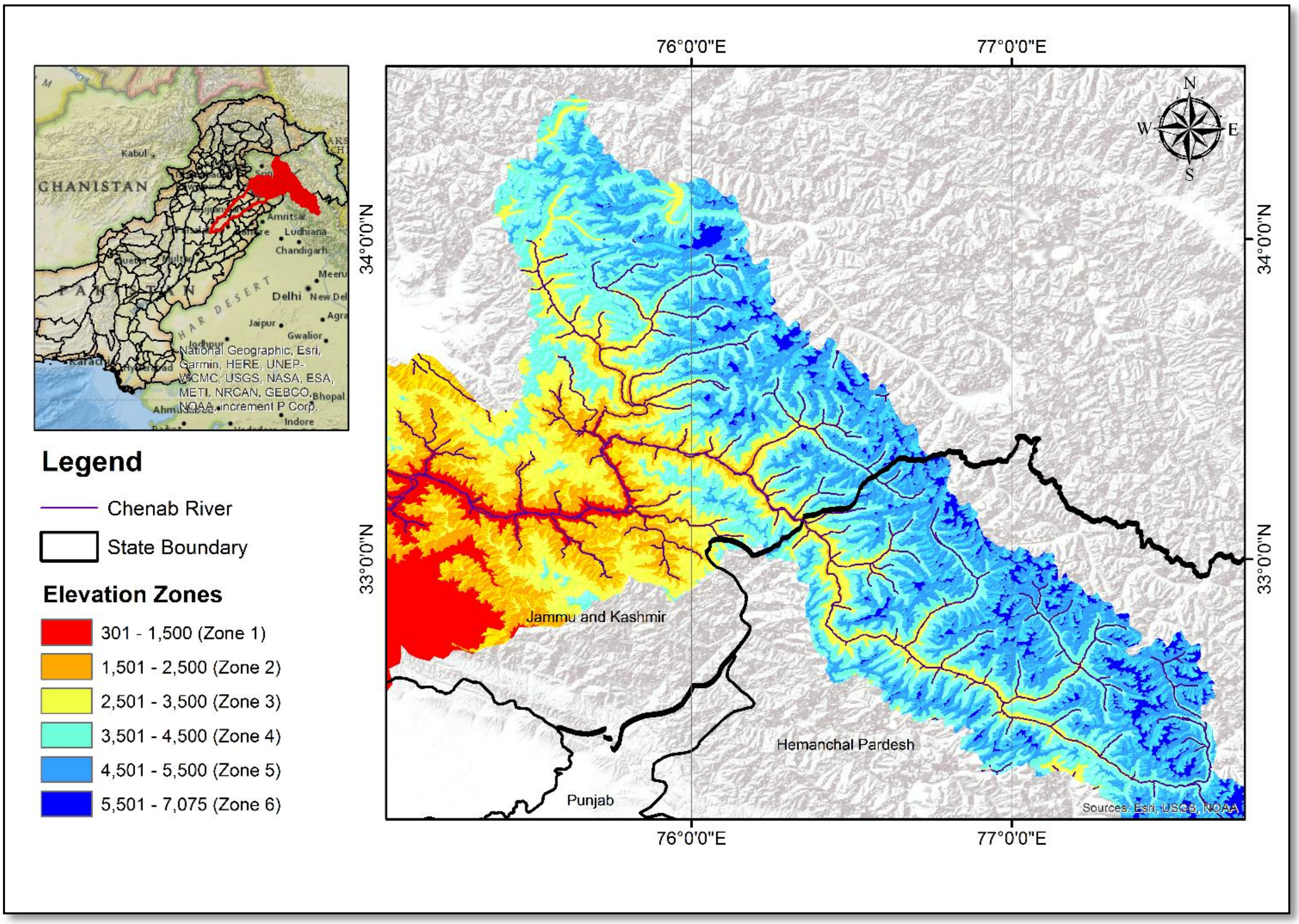


Figure 3: Elevation zones extracted based on SRTM DEM (30m) for Snow melt runoff modeling.

3.2.4.1 Snowmelt Runoff Modelling

Snowmelt Runoff Model (SRM) is one of the frequently used hydrological models for high altitude catchments. The model has been used to estimate snowmelt runoff in many watersheds and basins, including the Beas, Lidar, and other basins. Apart from the monsoon season, when rainfall is a major contributor, all these studies have established that the snowmelt contribution is the primary source of discharge in the basin, although the percentage contribution in runoff varies for different basins. The improved SRM model, (which Bookhagen and Burbank constructed using satellite-derived data) predicted that snowmelt will contribute between 15 and 60 percent of runoff in the western Himalayas and less than 20 percent in the middle and eastern Himalayas. SRM was developed in 1975 by

Martinec and was used in small Basins in Europe. With the passage of time as remote sensing of snow cover (through satellites) techniques progressed, SRM is being used to assess the discharge in larger basins as well. The Snowmelt-Runoff Model (SRM) can simulate flow on daily basis in mountain basins in which snowmelt contributes to runoff. The parameters for the SRM model are Rainfall Contributing Area (RCA), temperature lapse rate, the degree-day factor, runoff coefficient, critical temperature, recession coefficient, and time lag. The variables of the SRM model are precipitation, snow cover and temperature. The basic equation behind the SRM is given as;

$$Q_{n+1} = \{[C_{Sn}.a_n (T_n + \Delta T_n) S_n + C_{Rn}.P_n].A.(10000/86400).(1-k_{n+1}) \} + Q_n k_{n+1} \qquad (4)$$

where:

Q = average daily discharge [m^3s^{-1}]

C = runoff coefficient expressing losses as ratio

a = degree day factor [cm $^0C^{-1}d^{-1}$]

S = ratio of snow covered area to the total area

P = precipitation contributing to runoff [cm]

A = area of basin or zone [km^2]

T = number of degree days [^{0}C d]

T = the adjustment lapse rate when extrapolating temperature from the station to average hypsometric elevation of the basin or zone [^{0}C d].

k = recession coefficient indicating the decline of discharge in a period without snow melt or rainfall.

n = sequence of days during discharge computation period.

SRM also uses Tcrit, a prescribed threshold temperature which determines whether the contribution is rainfall and immediate.

The flow chart for SRM is given in figure 4.

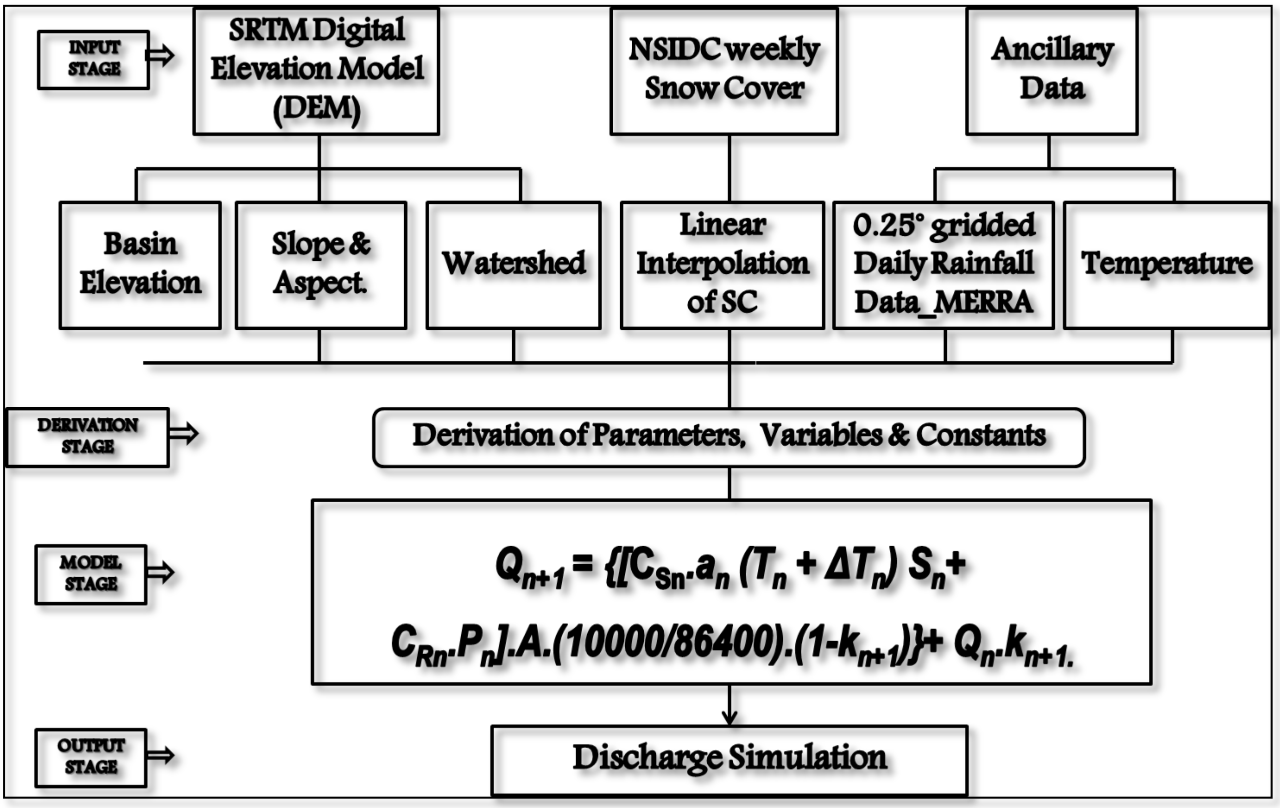


Figure 4: Flow chart showing processing of data in Snow Runoff Model

For effective simulation of discharge, determination of many parameters is required; for example, the rainfall (C_R) and snow (C_s) runoff coefficients along with degree-day factor (α). The initial values of all these parameters were taken from previous studies carried out in the basin or nearest basin i.e Jehlum. The initial values taken in this study were usually from Azmat, et. al. (2018).

In this study a temperature lapse rate of 0.65 was used and using this lapse rate mean temperature was calculated for each zone. The simulated discharge from SRM is primarily influenced majorly by snow cover area change and a little by the precipitation input, hence it is not necessary to estimate data of precipitation and temperature for each zone using a lapse rate. For each altitudinal zone, the average of the daily precipitation values of virtual gauging station located within zone was used. The daily zone wise snow-covered area was calculated by the linear interpolation of the snow cover area percentage estimated from weekly NSDIC dataset.

3.2.4.2 Assessment of contribution of Snow in Runoff

As the output from SRM gives a cumulative output in result of precipitation and snow and whereas the instant study focuses on estimating contribution of snow in runoff and variation of snow melt and resultant impact of runoff. Thus after successful run of SRM for calibration (1990 to 1995) and Validation (1995-2000), the model was run with option of “0” for Rainfall Contributing Area (RCA).

3.2.5 Impact of climate variables on Runoff of the Chenab River basin at Marala

The regression analysis was done between precipitation, temperature, SCA, Snow melt acquired from SRM model and inflows at Marala are used to assess the relation between these variables.

a. **Multiple R**: It is r squared's square root. It shows how much the linear correlation is strong?. A value 1 is the ideal positive relationship, while value of 0 is absence of all relationships.

b. **R Squared**: The Coefficient of Determination, or r^2 provides the number of points which fall on the regression line.

c. **R square adjusted**: It corrects for a model's variable count.

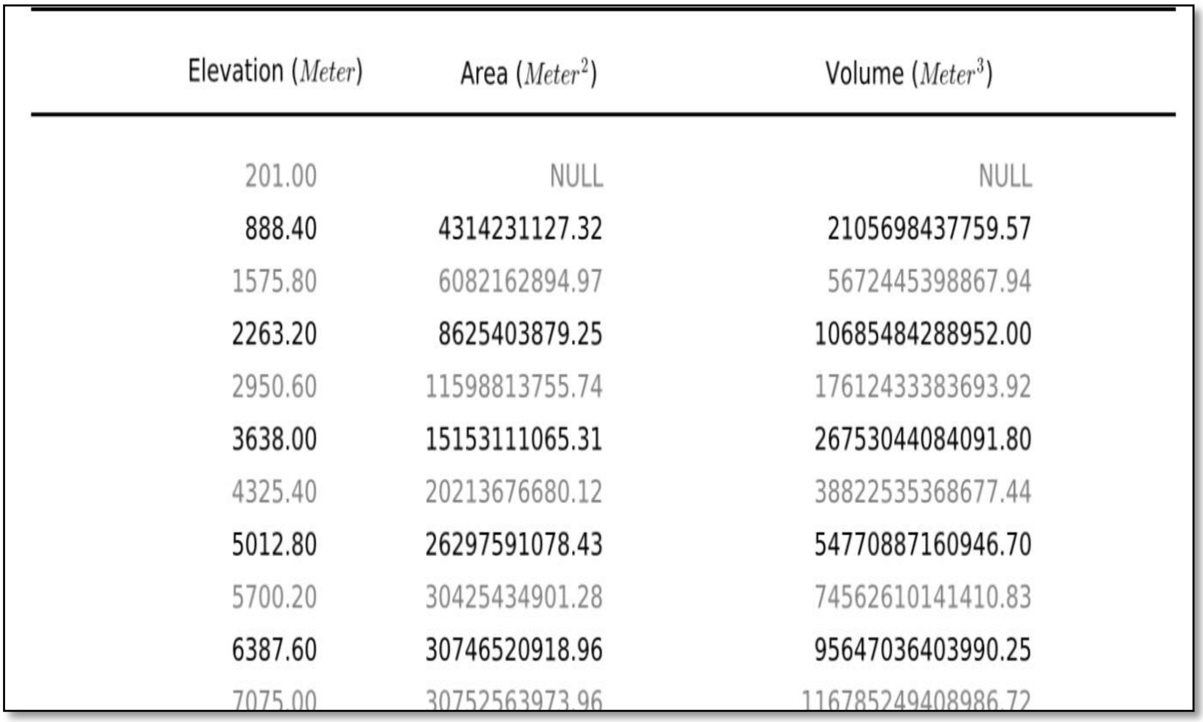
Chapter 04

RESULTS AND DISCUSSIONS

4.1. Storage Capacity Available in Chenab River Basin

The study made use of “Storage Capacity Tool” available in “Arc GIS”, to assess the water storage capacity across the whole Chenab basin at different elevations. Storage capacity across different elevation is given in the following figure.

Table 3: Storage capacity in Chenab Basin as per “Storage Capacity Tool” computed using elevation data of basin.



Elevation (*Meter*)	Area (*Meter*^{2})	Volume (*Meter*^{3})
201.00	NULL	NULL
888.40	4314231127.32	2105698437759.57
1575.80	6082162894.97	5672445398867.94
2263.20	8625403879.25	10685484288952.00
2950.60	11598813755.74	17612433383693.92
3638.00	15153111065.31	26753044084091.80
4325.40	20213676680.12	38822535368677.44
5012.80	26297591078.43	54770887160946.70
5700.20	30425434901.28	74562610141410.83
6387.60	30746520918.96	95647036403990.25
7075.00	30752563973.96	116785249408986.72

The result of analysis shows that out of all available storage capacity more than 0.6 MAF has already been harnessed. Whereas the cascade of development planned on Chenab basin will further enhance the usage of available storage capacity beyond 0.6 MAF. As per preliminary examination of available storage capacity and already harnessed capacity, it has been evaluated that India has harnessed almost 0.6 MAF which is maximum allowed limit under Indus Water Treaty (1960). Any further development will further increase this figure.

4.2. **Analysis of Existing projects in Chenab and variations in Flows**

As per available literature and published reports, it has been found that there is cascade of development which is planned in Chenab Basin within territorial jurisdiction of in India. According to estimates currently there are 25 run off river projects which are under planning stage and three projects such as Dulhasti Dam, Baglihar I&II and Salal I&II are already completed. The spatial distribution of above referred projects is given in Figure 6. The detail related to each project such as storage, power generation capacity is given in Annex A.

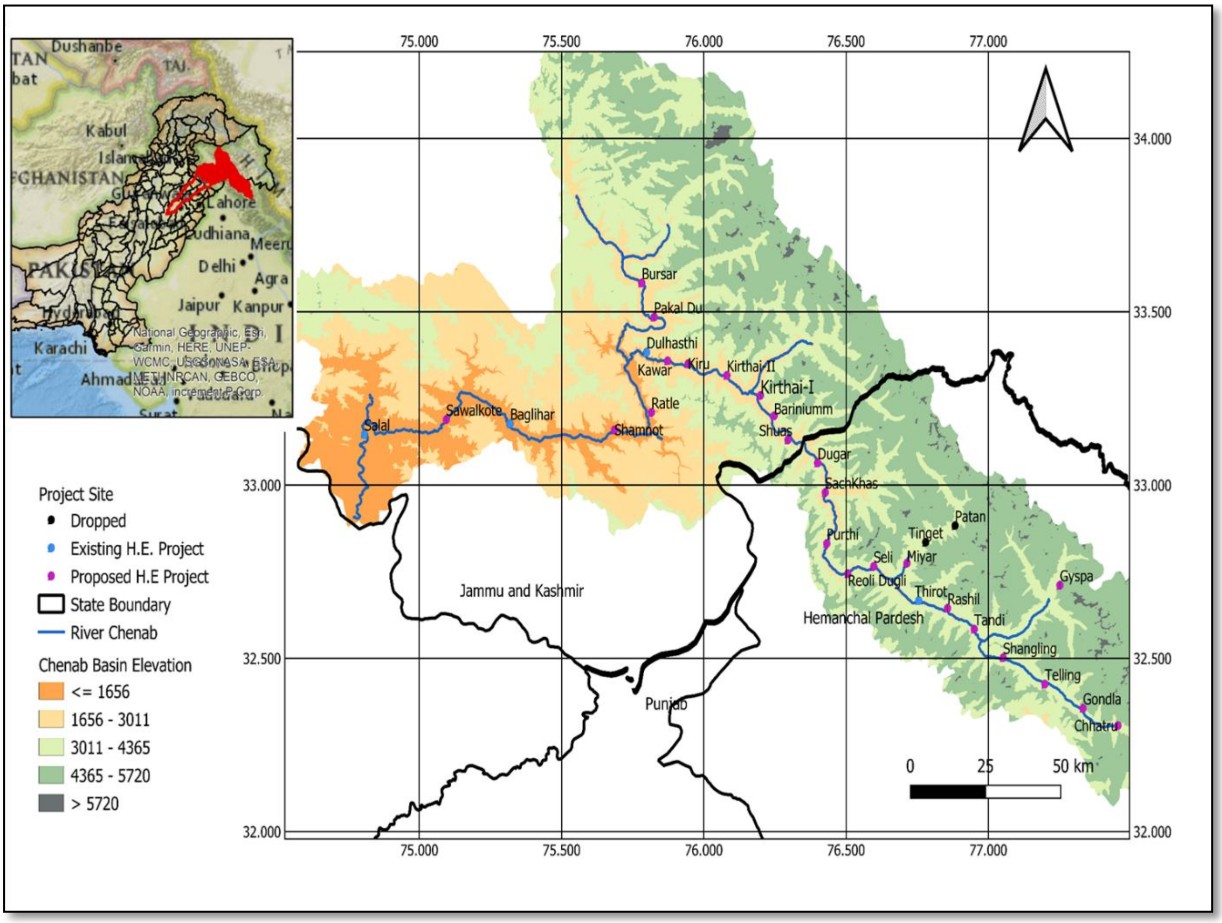


Figure 5: Cascade of development in Chenab Basin by India starting from Hemanchal Pardesh to Jammu & Kashmir.

4.2.1 Comparison of allowed vs Available Storage in Chenab Basin under IWT

Annexure E of Indus water treaty defines the limit of various use of water from western River. As per annexure e, India can use 0.6 MAF for power storage at Chenab main, however as per already published literature and assessment of storage capacities, it has been found that the three operation projects (i.e Salal, Dulhasti and Baglihar present on Chenab main tributary) have a power storage of almost 0.62 MAF which means the limit has already been achieved and if any further development is done then definitely there will be more use which will go beyond the prescribed limit of Indus water treaty (detail given in Table 3).

Table 4: Comparison of allowed vs available Storage in Chenab Basin under IWT

Dam on Chenab Main	Gross Storage (MAF)*	Allowed General Storage(MAF)	Allowed Power Storage (MAF)
Salal I	0.007	0.5	0.6
Salal II	0.22		
Dulhasti	0.0094		
Baglihar I&II	0.385		
Total	0.6214		

* Source: National Register of Large Dams - Central Water Commission India & Indus water Commission

4.3 Variation in River Flow at Marala

As per assessment, there is an over all decrease in flows at Marala. In this study, a comparative analysis has also been done for Before and After Dam construction scenario. If we compare current volume of inflows at Marala with flows in 1961, there is more than 32 percent decrease in flows. There is almost more than 38 % decrease in flows as compared to 1990's level. Moreover, when annual flows are compared with storage capacities of project it has been assessed that there is significant negative correlation at 95 % confidence level (i.e P= <0.05) as given in Table 4.

Table 5: Correlation of average annual storage and annual Inflows at Marala

	Coefficients	***Standard Error***	***t Stat***	***P-value***	***Lower 95%***	***Upper 95%***	***Lower 95.0%***	***Upper 95.0%***
Storage	-0.5	0.2	-2.8	0.02	-0.9	-0.1	-0.9	-0.1

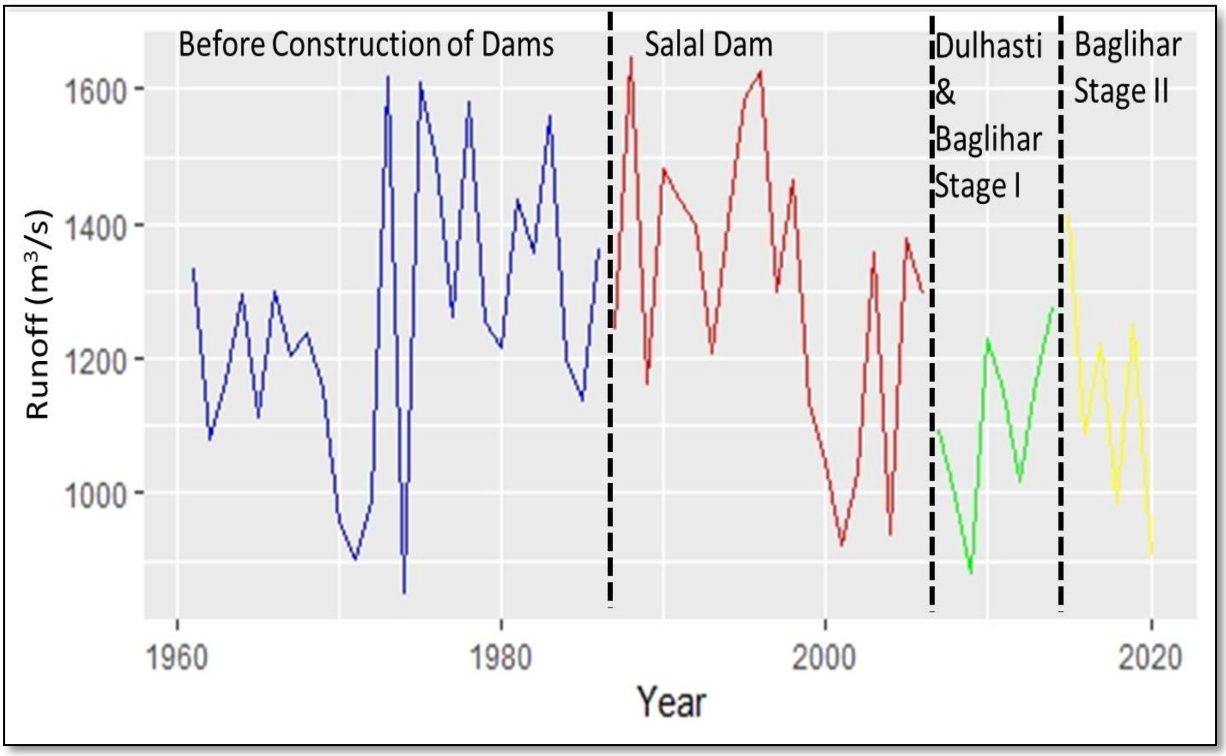


Figure 6: Variability in annual flows at Marala from 1960 to 2020 before nad after dam construction in the catchment.

The trend Analysis of inflows was carried out on Annual and seasonal basis and it has been shown that there is significant decrease in inflows between April till June and annual flows, however in winters there is significant increase in flows. Decrease in flows in annual and during summers is also shown by other studies such as Khattak et al., (2011), Ahmed et al., (2018) & Dimri et al, (2018). At a confidence level of 95 %, value of p is significant (i.e <0.05) for annual, Snow melt Season and winters.

Table 6: Results of Man Kendall Trend analysis for Inflows at Marala

Season	**Kendall's tau**	**p-value**	**Sen's slope**
Annual (Jan- dec)	-0.131	**0.001**	-0.057
Winter (December-January))	0.108	**0.017**	0.004
Pre-monsoon (March -May)	0.003	0.963	0.002
Monsoon	-0.238	**0.001**	-0.050
Post-Monsoon (September-November)	-0.070	0.072	-0.007

Figure 8 (a) shows that over the span of record, annual historical inflows on the Indus have been dropping (significant at 95 percent). Contrary to popular belief, an increase in flow would not be related to rising temperatures, precipitation, and expected rises in melt waters (as discussed in Archer et al. 2010). Same is the case with other seasons i.e an overall decreasing trend is shown however significant decrease is shown in monsoon and winter season.

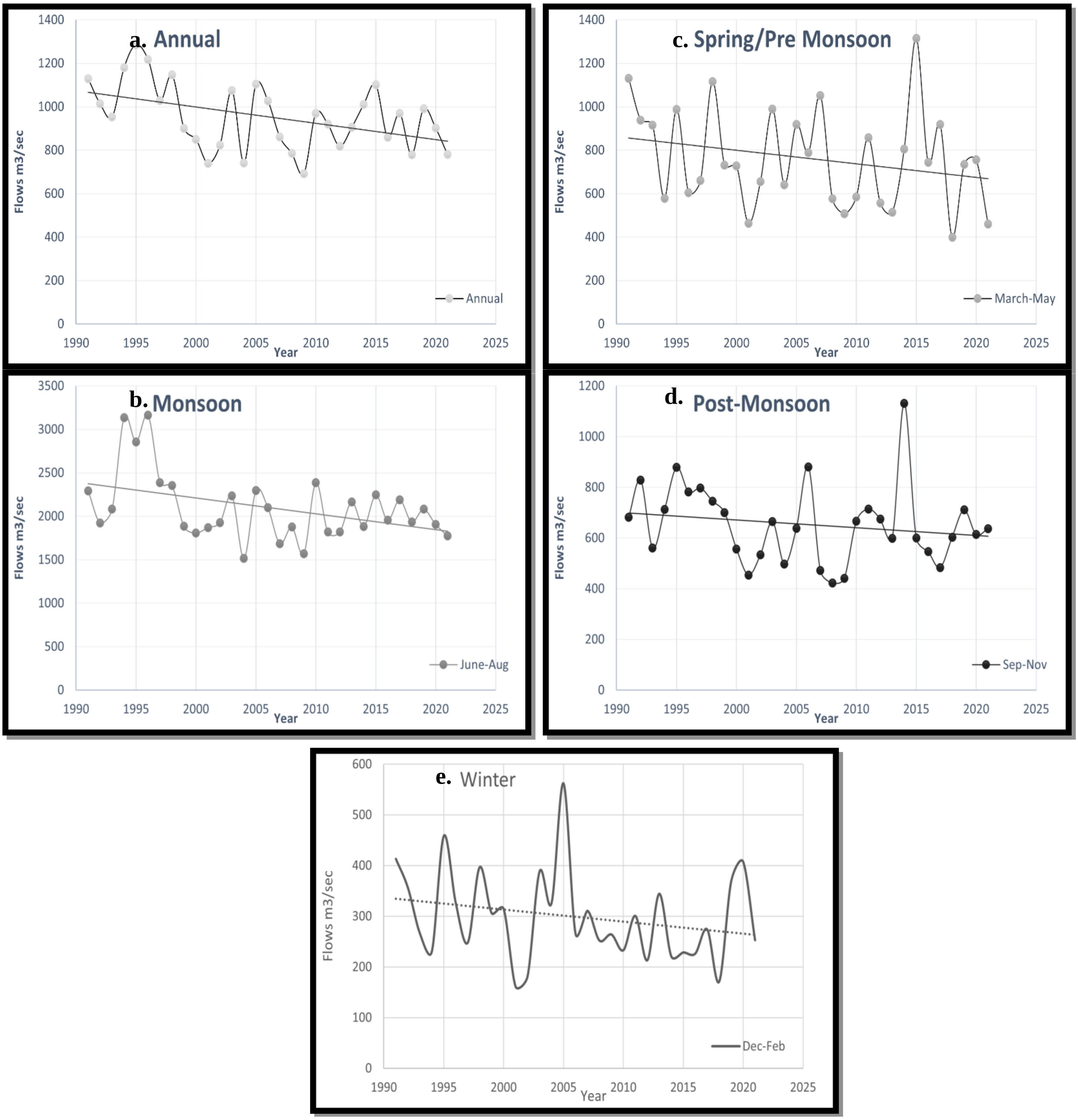


Figure 8: The figure (a-e) is showing the Seasonal Trend in flows at Marala based on Man Kendall Trend Test.

4.4 Evaluation of Datasets

To eliminate any biasness in study for storage being the reason of for decreasing flows at Marala, it was necessary to assess other parameters such as precipitation and Snow cover as well. Therefore, among the two datasets for precipitation i.e. TRMM and MERRA-2, the data of MERRA 2 was selected based on evaluation by means of RMSE and Correlation Coefficient. Results of validation are given in Table 5. As per stats the MERRA-2 has performed better than TRMM in present case. Due to variation in topography and presence of western mountains, the gridded products may not assess the ground situation precisely (Pour et al., 2014). The improved precipitation estimates of MERRA-2 near-surface air temperature and humidity are due to coupled atmosphere–land modeling system (Reichle, et. al., 2017).

Table 7: Results of Validation of Precipitation Products

Ground Station		TRMM	MERRA-2
Kotli	CC	0.359508	0.76973
	RMSE	4.111428	3.261058
Gujrat	CC	0.282693	0.883226
	RMSE	4.244871	1.307622
Jhelum	CC	0.296108	0.769413
	RMSE	4.668215	2.366953
Sialkot	CC	0.38202	0.87704
	RMSE	4.794406	1.717493

4.5. Trend Analysis of Precipitation

Trend in the data of precipitation was evaluated using Man Kendall Trend Test across the whole Chenab Catchment. Eleven virtual gauging points, after careful validation of MERRA-2 data, were selected to assess the precipitation trend.

As per trend analysis based on MERRA-2 daily precipitation estimates, there is significant positive trend in Annual precipitation across the Chenab basin. When it comes to seasonal precipitation there is significant increase (i.e. p-value < 0.05) during June to August at few points as shown in Table 7. All significant figures are highlighted in the table.

However for the time period of January to December, 7 of the 11 virtual gauging points are showing significant increase as P-value is less than 0.05. Detail of trend analysis is given in Table 7.

Based on analysis of precipitation trends it is very clear that there is no decreasing trend in precipitation being observed in past thirty years data, which is significant and can explain the decreasing trend of runoff at Marala. There is no negative trend across all virtual gauging points whether it be significant or non significant as no negative values of Kendall’s tau are observed in any of four season in the period under investigation.

Therefore the notion of precipitation changes being reason of variation in flows is out of question and does not justify this stance as the data shows significant positive trends specifically in monsoon season while the data of discharge has shown significant decline in monsoon and winter flows at Marala.

Table 8: Results of Precipitation Trend Analysis

	Annual (Jan-Dec)			Post-Monsoon(Sep-Nov)			Monsoon(Jun-August)			Pre-Monsoon(March-May)			(Dec-Feb)		
Virtual Gauging Station	Sen's Slope	P-value	Kendal's Tau	Sen's Slope	P-value	Kendal's Tau	Sen's Slope	P-value	Kendal's Tau	Sen's Slope	P-value	Kendal's Tau	Sen's Slope	P-value	Kendal's Tau
Point1	0.02	0.09	0.26	0.01	0.50	0.11	0.06	0.09	0.26	0.03	0.09	0.23	0.00	0.96	0.01
Point2	0.05	**0.01**	0.36	0.02	0.19	0.17	0.05	0.12	0.20	0.03	0.46	0.10	0.03	**0.01**	0.32
Point3	0.03	**0.00**	0.43	0.01	0.30	0.14	0.02	0.07	0.24	0.02	0.25	0.15	0.03	**0.01**	0.36
Point4	0.04	**0.01**	0.36	0.02	0.25	0.15	0.07	**0.04**	0.27	0.03	0.05	0.26	0.02	0.10	0.21
Point5	0.05	**0.01**	0.34	0.02	0.13	0.20	0.06	**0.04**	0.27	0.04	0.06	0.25	0.03	0.09	0.22
Point6	0.05	**0.01**	0.33	0.02	0.09	0.22	0.06	**0.04**	0.26	0.04	0.11	0.21	0.03	0.05	0.25
Point7	0.04	**0.03**	0.29	0.02	0.06	0.24	0.05	**0.03**	0.28	0.04	0.15	0.19	0.03	**0.03**	0.28
Point8	0.04	**0.01**	0.33	0.02	0.07	0.23	0.04	0.05	0.25	0.03	0.25	0.15	0.03	**0.01**	0.35
Point9	0.04	**0.01**	0.34	0.02	0.07	0.23	0.03	0.09	0.22	0.04	0.12	0.20	0.03	**0.05**	0.26
Point10	0.03	**0.01**	0.33	0.02	0.05	0.26	0.02	0.11	0.21	0.03	0.11	0.21	0.03	**0.04**	0.27
Point11	0.03	**0.02**	0.31	0.02	0.05	0.26	0.01	0.35	0.12	0.03	0.09	0.22	0.03	**0.03**	0.28
Mean	0.04	0.02	0.33	0.02	0.16	0.20	0.04	0.09	0.24	0.03	0.158	0.20	0.03	0.12	0.26

4.5 Snow Melt Modeling

4.5.1 Calibration and Validation of Model

The SRM was calibrated using data of runoff for period of Five years i.e. 1990-1995. After a number of runs the parameters were optimized and validation was done for next five years i.e. 1996-2000. The reason for selecting 1990's decade as calibration and validation period, lies in the fact that the flows till this decade were somewhat stable and after 2000 there is sharp decrease in inflows at Marala. The optimized parameters for during calibration are given in table 8. Results of calibration are given in Table 9.

Table 9: Calibrated Parameters for SRM

Parameter	Value
Critical temperature	2
Rainfall Coefficient	0.1-0.2
Snow Coefficient	0.15-0.3
RCA	1 for Pre-monsoon to Monsoon
Lapse Rate Temp	0.64
Xc	1.06
Yc	0.02
Lag Time	Zone wise 10-24 hrs (a total of 89 hrs calculated as per Synders relation)

Table 10: Results of Calibration and Validation

Period	Year	Measured inflows (m^3)	Computed inflows (m^3)	Volume Difference	% Volume Difference	Pearson's Correlation
Calibration Period (1990-1995)	1991	1815.67	1824.82	-9.15	-0.50	0.98
	1992	1576.55	1680.83	-104.28	-6.61	
	1993	1533.47	1592.94	-59.47	-3.88	
	1994	2064.54	2202.7	-138.16	-6.69	
	1995	2062.77	2108.81	-46.04	-2.23	
Validation (1996-2000)	1996	2003.44	2059.82	-56.38	-2.81	
	1997	1715.24	1732.92	-17.68	-1.03	0.99
	1998	1805.92	1976.22	-170.3	-9.43	
	1999	1475.04	1504.18	-29.14	-1.98	
	2000	1369.37	1393.76	-24.39	-1.78	

4.5.2 Contribution of snowmelt in Runoff in Chenab River Basin

To assess the contribution of snow melt, the option of RCA was kept zero and SRM was run for Snow melt period. The results have shown that the higher flows in July and August during the snowmelt period i.e. April to September. The reason of high flows in these months is increased temperature and increased monsoon precipitation which triggers more snow melt in the season.

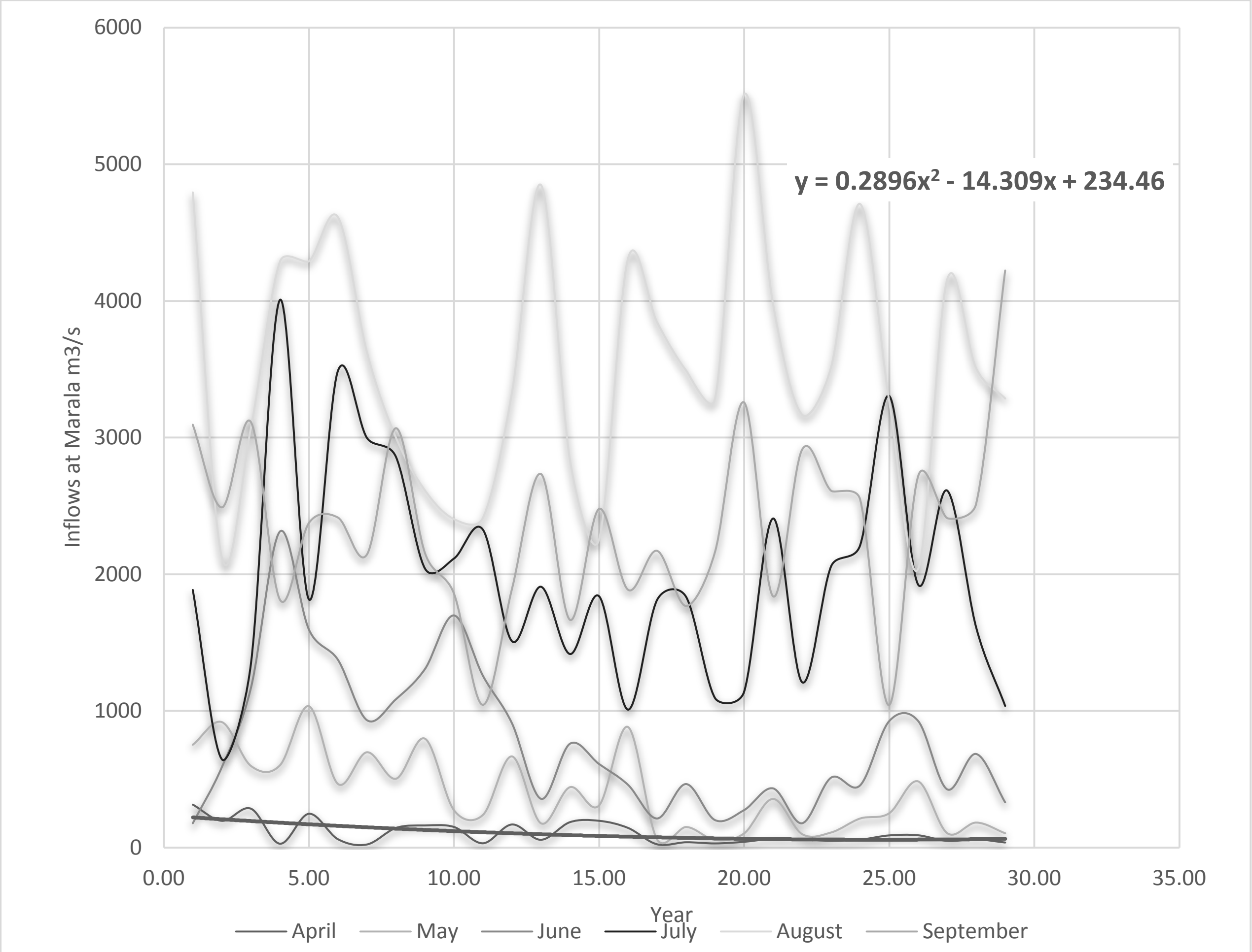


Figure 9: In-Flows at Marala: Contribution of Snow Melt (1990-2020) during month of April till September

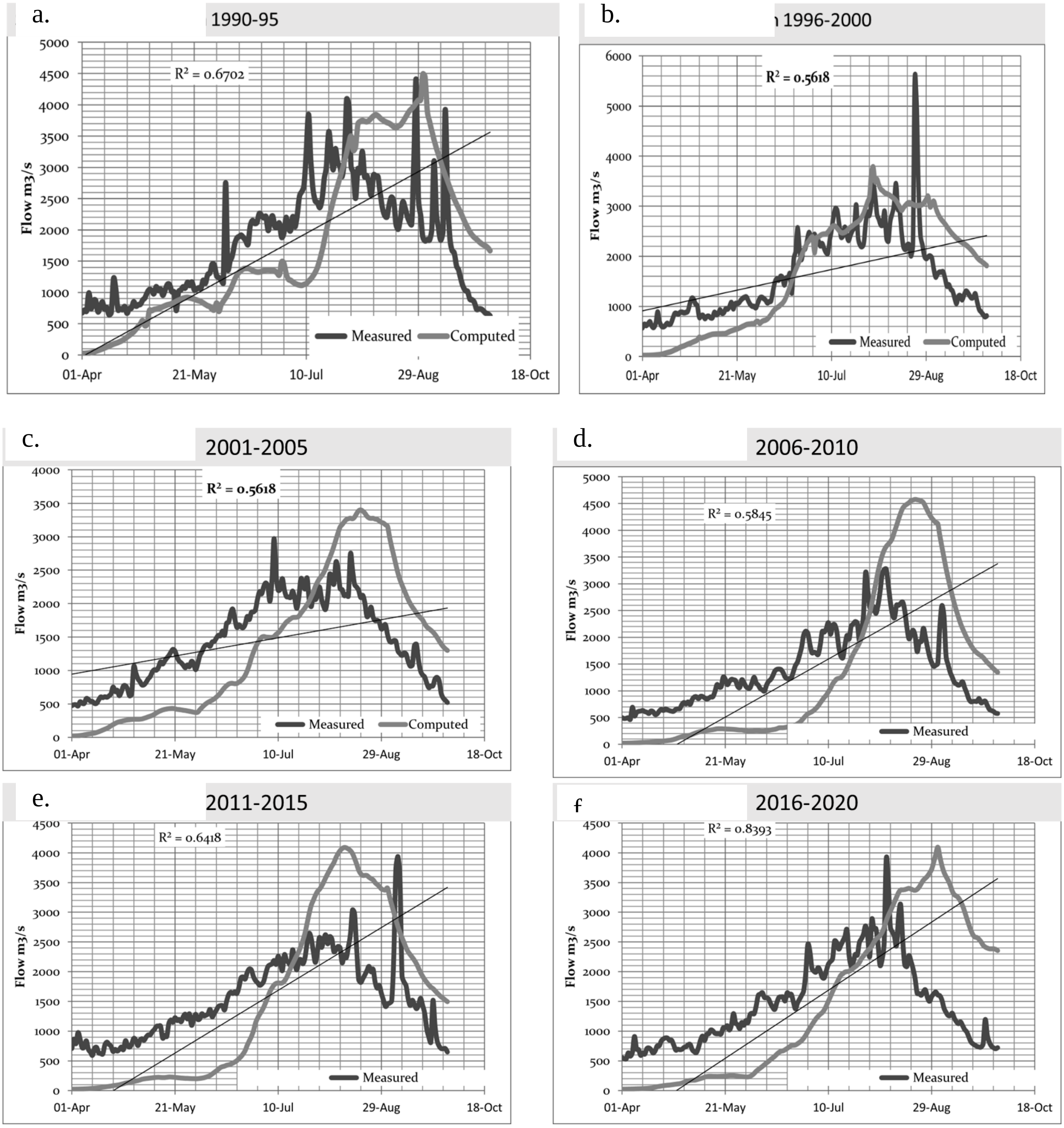


Figure 7(a to e): Snow-melt contribution 1990-2020

4.6. Impact of climate variables on Runoff of the Chenab River basin at Marala

Regression analysis was done to assess the relation of different parameters such as daily precipitation, temperature, Snow covered area and Snow melt computed from SRM. The temperature and precipitation values used in this regression were calculated through area average method from data of virtual gauging points of MERRA reanalysis data set. The analysis has shown that no significant relation was drawn on the basis of regression analysis. The detail is given in table 10. The results have shown that the regression model explains more than 60 percent of relationship between independent and dependent variables.

Table 11: Result of Regression Analysis

	Coeff.	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	4011.1	1031.4	3.9	0.0	1886.9	6135.3	1886.9	6135.3
Precipitati	33.0	75.2	0.4	0.7	-121.8	187.8	-121.8	187.8
Temperat	-239.9	82.4	-2.9	0.1	-409.6	-70.2	-409.6	-70.2
SRM	0.8	0.4	1.9	0.1	-0.1	1.8	-0.1	1.8
SCA	0.0	0.0	0.3	0.8	0.0	0.1	0.0	0.1

Table 12: Multiple linear Regression Statistics

Statistics	**Value**
Multiple R	0.643742
R Square	0.414404
Adjusted R Square	0.3
Standard Error	172.681
Observations	10950

As per acquired results, none of the independent variable is affecting significantly to the dependent variable i.e., run off. These results show that variability in flows at Marala may not be explained by any of the parameters given in Table 11.

CONCLUSIONS & RECOMMENDATIONS

5.1. Conclusion

This study used observed inflows at Marala, planned and existing storage in Chenab basin and climatic measurements including estimates of snow melt contribution to assess the variability of inflows at Marala. A number of correlation analysis and regression was performed to explore the linkage between inflows and other hydro-climatic parameters. Following conclusion is drawn on the basis of results of studies.

1. Existing power storage capacity in Chenab Basin is already being used as allowed by Annexure E of Indus water Treaty.
2. There is significant decrease in Annual Flows at Marala and flows during months of June to August. However, there is increasing trend in winters. The overall significant decrease in Annual flows show that the annual flows are influenced by variations in flows during months of June, July & August. When linear regression was applied on annual flows and storage capacity of existing project, significant correlation was found which means that decrease in flows is significantly correlated with increase in storage for hydro power project.
3. Trend Analysis of precipitation have shown significant Annual increase along with winters across the Chenab basin. No significant decreasing trend as found at any virtual gauging point. At some points there is significant increase in precipitation during (Monsoon or June July &August). The increase in precipitation arises questions on decreasing annual flows at Marala because increase precipitation must contribute to increasing flows. It can be concluded that the decreasing flows at Marala are not influenced by precipitation.

4. The snow melt contribution reaches to maximum in the month of July & August. This increase can be attributed to cumulative influence of temperature and monsoon precipitation which triggers melting
5. The regression analysis of climatic and hydrological variables (using Inflows as dependent variable and precipitation, temperature, SCA and snow melt as independent parameters) have shown no significant correlation which can draw any inference regarding decreasing flows at Marala.

5.2. Recommendations

There is dire need of active policy making and active participation for implementation of Indus water treaty. Only a strong and well planned strategy can resolve the water sharing issues between India and Pakistan.

Increasing the number of climatic station within the catchment is also needed. As per IWT data regarding flows is bound to be shared but unfortunately that data is not available easily for research purpose. It is therefore recommended that real time data availability for public may be assured.

The majority of Chenab catchment lies in India and there are climatic station present in upper catchment, however the data of those stations is not available. It is therefore recommended that policy makers must address the issue of real time data availability for better research.

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ANNEXURES

Table 13: Appendix 1: Detail of Indian hydro power projects in entire Indus river basin.

Indian Hydropower Projects in Indus River Basin									
Sr #	**Name**	**Latitude**	**Longitude**	**Year of completion**	**River**	**Height (meter)**	**MW capacity**	**Length (meter)**	**Storage capacity (cubic meter)**
1.	Baghliar I & II[i]	33.16257	75.3272	2009 & 2015	Chenab	143	900	363m	475000000
2.	Barinium	33.16038	76.28654	Environment clearance awaited	Chenab	117	240.00	Not available	Not available
3.	Bursar	33.65168	75.71548	Environment clearance awaited	Chenab	289	800	6.75 Km	616744500
4.	Chahtru Barrage (hemachal pardesh)	32.31953	77.36438	Environment clearance awaited	Chandra river (Tributary of Chenab)	19	126		875000
5.	Chenai HEP	33.03164	75.28431	Environment clearance awaited	Chenab	Not available	Not available	Not available	Not available
6.	Chutak Barrage	34.49	76.11306	2013	Indus	15	44.00	43	588000
7.	Deothal (himachal pardesh)	32.67028	76.37444	Environment clearance awaited	Ravi	668m head	30	25	1674
8.	Dugar Reservoir (Hemachal Perdesh)	33.11806	76.35575	Environment clearance awaited	CHENAB	128	449	214	615800

Sr #	Name	Latitude	Longitude	Year of completion	River	Height (meter)	MW capacity	Length (meter)	Storage capacity (cubic meter)
09.	Dulhasti Dam	33.36667	75.66667	2007	Chenab	65	390	186	11700000
10.	Gondhala	32.50423	77.02187	Environment clearance awaited	Chenab	Not available	144	Not available	Not available
11.	Gyspa Reservoir	32.6575	77.20694	Environment clearance awaited	Chenab	200	300		912781860
12.	Kawar HEP	33.35028	75.89417	Environment clearance awaited	chenab	109 m high	560	195	27167000
13.	Keeru HEP	33.3409	75.9492	Environment clearance awaited	Chenab	135m	660	6.5 km long	41500000
14.	Kirthai I	33.25972	76.16944	Environment clearance awaited	Chenab	147.5 m	390.00	160 m HRT	104500000
15.	Kirthai II	33.31139	76.07694	Environment clearance awaited	Chenab	121	930.00	219m	17000000 (live storage)
16.	Kishan Ganga	34.3968	73.7181	2018	Jhelum	37	330.00	140	2100000000
17.	Lower Kalnai Barrage	33.135	75.75833	Environment clearance awaited	Chenab	49	48	3.96 Km long RT	Not available

Sr #	Name	Latitude	Longitude	Year of completion	River	Height (meter)	MW capacity	Length (meter)	Storage capacity (cubic meter)
18.	Miyar HEP	32.76889	76.7075	Environment clearance awaited	Chenab	27	120	232m	900000 (live storage)
19.	Nimo Bazgo	34.21472	77.18528	2013	Indus	59	45.00	247	52820000
20.	Purthi	32.90356	76.4625	Environment clearance awaited	Chenab	63	232	Not available	Not available
21.	Rashil	32.58995	76.88945	Environment clearance awaited	Chenab	18m	130	8.8 km	Not available
22.	Ratle Dam	33.16514	75.80184	Environment clearance awaited	Chenab	133m	850	189.5	78710000
23.	Reoli Dugli	32.82672	76.40054	Environment clearance awaited	Chenab	54m	429	127m	11400000
24.	Sach Kas	32.96531	76.42504	Environment clearance awaited	Chenab	77	267 MW	241.5	25240000 (live storage)
25.	Salal HEP a. Gravity Filled dam b. B. concrete dam	33.14194	74.80861	1987	Chenab	118 112	690 MW	630 450	8790000 272070000
26.	Seli Plant	32.76166	76.53666	Environment clearance awaited	Chenab	80	400	189.5	8223000

Sr #	**Name**	**Latitude**	**Longitude**	**Year of completion**	**River**	**Height (meter)**	**MW capacity**	**Length (meter)**	**Storage capacity (cubic meter)**
27.	Shangling (alotted in 2011)	32.4986	77.04557	Environment clearance awaited	Chenab	Not available	44	Not available	Not available
28.	Shamnot	33.155	75.70439	Environment clearance awaited	Chenab	Not available	370	Not available	Not available
29.	Shuas	33.13034	76.31085	Environment clearance awaited	Chenab	Not available	230.00	Not available	Not available
30.	Sawalkot	33.18333	75.1	Environment clearance awaited	Chenab	193m	1856.00	Not available	530000000
31.	Tandi	32.5534	76.97428	Environment clearance awaited	Chenab	Not available	104	Not available	Not available
32.	Telling	32.44408	77.15955	Environment clearance awaited	Chenab	Not available	94	Not available	Not available
33.	Thirot (commissioed in 1995)	32.69025	76.79945	1995	Indus	Not available	4.5	Not available	Not available
34.	Uri I & II HEP	34.09139	74.03222	1997 & 2014	Jhelum	a. 21.5 b. 44	240.00	a. 95 b. 175	309000 b. 6343000
35.	Wullar Dam	34.2888	74.5115	Construction started in 1984	Jhelum	1.37		439 feet	370046700

Sr #	**Name**	**Latitude**	**Longitude**	**Year of completion**	**River**	**Height (meter)**	**MW capacity**	**Length (meter)**	**Storage capacity (cubic meter)**
36	Pakaldul	33.45833	75.81389	Environment clearance awaited	Chenab	167	1000	305	125400.00000000001
37	Patam	32.88417	76.87879	dropped	Chenab	Not available	65	Not available	Not available
38	Tinget	32.84092	76.76706	dropped	Chenab	Not available	145	Not available	Not available

(Note: Pakal Dul (1000 MW) Kiru (624 MW) Kwar (540 MW) Sawalkote (1856 MW) Kirthai-II (930 MW) Kirthai-I (390 MW) Shamnot (370 MW) Miyar (120 MW) Chhatru (126 MW) Seli (400 MW) Sachkhas (267 MW) Dugar (449 MW) Reoli Dugli (420 MW) Gyspa (300 MW) Bursar (800 MW) have been recommended for revision while Tinget and patam are dropped)
