ANALYSIS OF HYDROCLIMATIC VARIABILITY AND ADEQUACY OF CHANNEL FLOWS IN AN ARID ZONE IN PAKISTAN

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Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Water Resource Engineering and Management

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DECLARATION

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Date

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ABSTRACT

ANALYSIS OF HYDROCLIMATIC ADEQUACY AND VARIABILITY OF CHANNEL FLOWS IN AN ARID ZONE OF PAKISTAN

Water is becoming progressively scarce and effective usage of accessible supplies is of major concern. Globally, 15% ~ 21% of the water allocated for irrigation is lost due to poor management and non-optimized conveyance practices. Pakistan is an agricultural country which hosts one of the world's largest irrigation networks, Indus Basin Irrigation System (IBIS). The system has been found to operate with an irrigation efficiency of a mere 35% ~ 50% which is abysmally low. It is thus vital to oversee the proper management of this scarce resource while limiting the losses within the system. The selected Hakra canal covers an irrigated area of 2031 km^2 with a 92 km of total length and lies in the semi-arid region in Punjab, Pakistan.

The aim of the present study is to evaluate the competence of the available irrigation channel flows to meet actual Crop Water Requirement (CWR) and variations in availability with climatic irregularities. For the detailed analysis of hydroclimatic variability and channel flow adequacy, data of daily channel flows and climatic parameters were obtained for the period of 2010~2017 while monthly rainfall data from 1978~2017 was used for long-term trend analysis. The CWR was estimated using CROPWAT 8.0. Observed deficit in supply is provided by groundwater abstraction and was estimated using root zone water balance approach. Mann-Kendall and the Sen's slope tests were used to detect the possible trend and its magnitude. An upstream rainfed basin is selected and used for the verification of observed climatic variations.

Trend analysis depicted an increase in annual rainfall from 1978~2017 over the region with the estimated contribution of 13% to irrigation supply. Irrigation supplies are the dominating source of water and highly fluctuating. The seasonal shortfall has shown a variation of 7%~26% in Rabi season and 71% ~78% in Kharif season. Further analysis of data revealed an increasing trend in the maximum and minimum temperature values especially in the months where rainfall has also shown an increase i.e. June and September.

The observed climatic variability in the downstream of IBIS is highly reliant on hydrological behaviour of upstream catchments. Four parameter '*abcd*' lumped model with incorporated snow parameter '*m*' for icy catchment is used to sensibly screen and verify the reaction of a catchment under the climate change scenario by evaluating the changes in hydrological processes. The better understanding of meteorological and hydrological conditions of the study area helped proper investigation and imitation of the actual situation. Unreliable supply of water in the irrigation system along with variability in climatic factors i.e. precipitation and temperature would disturb the dynamics of hydrological water cycle hampering crop yield. It would elevate the maximum soil moisture deficit that results in crop failure or low yield.

Keywords: Alternating crop pattern; Channel flow optimization; Crop water requirement; Hakra canal

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Overview

With the appealing demand of water around the globe, Irrigation networks particularly require attention, where broad entireties of water are wasted due to poor control and management (Ooi, Krutzen, & Weyer, 2005). Globally, 15~21% of the water allocated for irrigation purposes is lost due to poor management and conveyance practices (Salahou, 2013).

Indus Basin Irrigation System (IBIS) is a continuous supply-based system working on an official rotational plan for water distribution at secondary and tertiary level. Disagreement regarding the validity and effectiveness of a rotational plan still exists despite its wide use. Water allocation in IBIS, Pakistan is dependent on the design capacity of the canal and has a typical value of 2 mm/day. Many components of the system are water deficient and unable to accommodate the seasonal demand variations. Most of these are in the south-eastern part of the country with a low slope (Bandaragoda & Ur Rehman, 1995).

There is uncertainty regarding future water availability in the Indus basin, with the projections based on different climate models. Existing settings depict an exacerbation of the situation in forthcoming years with population explosion and spread of irrigated lands. Cropland class of land use has shown a significant increase over the past period. The overall increase is around 55% from 1947-48 ~ 1999-2000 as per the findings of Agricultural Statistics of Pakistan for 1999-2000. The Food and Agriculture Organization (FAO) in 2003 reported an annual increase rate of 0.3~0.4% for croplands (Khan, 2004).

Groundwater usage in Pakistan ranks 4th among all countries after India, USA, and China (Bhatti, Anwar, & Aslam, 2017).

Currently, a large part of IBIS is also relying on groundwater for its agriculture production either as the only source of water or coupling it with canal water (Bhatti et al., 2017; Usman, Liedl, & Kavousi, 2015). Previous studies have shown elevated groundwater abstraction from 9 BCM in 1965 to 45 BCM in 2002 due to a decline in the availability of surface water. Punjab province of Pakistan is dominating the use of groundwater and the development of private tube wells These conditions prevail especially in the southern district of Punjab, i.e. Bahawalnagar (Alam & Bhutta, 2004; Bhatti, Ahmad, Shah, & Khattak, 2019).

At present, more than 50% of the crop water requirement is being compensated by the groundwater abstraction when needed due to its flexible availability (Usman et al., 2015). Rice growing areas are majorly dependent on groundwater for irrigation purposes. Around 70 % of the irrigation water is obtained from the dug wells (Shafeeque, Cheema, Sarwar, & Hussain, 2016). Extensive global usage of groundwater has caused a drastic decline in the water table on a wider geographical area. Various parts around the country have shown 20% less recharge as compared to the abstracted amount of groundwater (Bhatti et al., 2019). The average annual drop rate of the water table in Pakistan is around 1~3 m/year, as the top users of groundwater, i.e. Eastern India, China, due to the high dependence of agriculture on groundwater (Usman et al., 2015). Especially, Punjab and Sindh provinces in Pakistan have shown an evident decline of the groundwater table in the past few years (Qureshi, McCornick, Sarwar, & Sharma, 2010). Extensive groundwater usage has also threatened the water quality by salinity particularly (Usman et al., 2015). Thus, in areas with prevailing semi-arid and arid conditions, water is the major limiting factor for crop production.

This study is focused on the analysis of water scarcity especially for the irrigation purposes in the perspective of future water management, evaluation of the climate change in the upstream of the basin and to quantify climate change impacts further on the water scarcity and suggesting the formulation of a hydraulic numerical model based on actual crop water requirement to ensure the effective distribution and management of available water. Based on prevailing unsteady flow conditions, unsteady flow analysis using HEC-RAS is recommended with the detailed evaluation of flow parameters of the Hakra canal with originally available irrigation channel flows and modified flows.

1.2 Problem Statement

Outstanding implications of existing water scarcity and climatic variability in Indus Basin Irrigation System (IBIS) requires necessary actions in terms of quantitative estimates of actual demands and hydrological effects of climate change.

1.3 Objective of the Study

1.3.1 Overall objective

Aim of the present research is to evaluate the Irrigation water adequacy based on actual demand and climate variability in Hakra canal system of Indus Basin Irrigation System (IBIS), Pakistan.

1.3.2 Specific objective

1. Identification of state of arts on the estimation of irrigation requirements and hydrologic modelling for climate variability
2. Assessment of actual irrigation requirements and adequacy of existing supply
3. Estimation of alternative input/third-party source if system supply is deficient
4. Analysis of climate variability in the area
5. Hydrologic modelling, analysis of climatic variability in upstream (u/s) basin and verification of observed results at downstream (d/s)
6. Recommendations for model applicability for climate change analysis and room for future work on hydraulic modelling

2 LITERATURE REVIEW

2.1 Introduction

Pakistan with semiarid to arid climate has almost 90% of its area under meagre rainfall. Only about 10% of the total area receives an adequate quantity of rainfall. On average, the country receives less than 240 mm of rainfall annually. Western disturbances and monsoon are the main sources of winter and summer rainfall, respectively, in the country. Western Disturbance entering from the neighbouring border of Afghanistan and Iran have their impact restricted to only northern and northwestern regions of the country, while the weather conditions entering from monsoon encompass most of the areas of the country. This variability is associated to both spatial and temporal scales as, southwestern part of the country receives a maximum amount of rainfall during the months of July to September due to monsoon while in the northern parts, the maximum rain falls through December to march (Rehman et al., 2012).

For the country, monsoonal rainfall is regarded as the major contributor in the annual water inflow with the share of almost 50-75%. The monsoon rainfall shows a significant variation of about 17~ 59% and it becomes dominant as it moves from humid areas in the northeast to arid area over the Indus basin in the southwest (Hussain & Lee, 2009; Rehman et al., 2012). Snow falling in the upstream of the country i.e. Upper part of Khyber Pakhtunkhwa province, Kashmir and northern areas significantly contribute in providing the essential source of water especially in dry weather conditions. Seasonal rainfall and snowfall not only support the agricultural system of the country but also helps in improving the socio-economic development (Muhammad et al., 2017).

2.1.1 Development of Indus Basin Irrigation System (IBIS)

Customarily, individuals adapt to this spatially uneven and rare distribution of precipitation by settling along the banks of the rivers or cautiously dealing with the local water reserves. This problematic, low-level harmony among man and water was unequivocally dealt with the novelty of large-scale irrigation system; i.e. Indus Basin Irrigation System (IBIS) in the nineteenth century.

The purpose of the Indus Basin irrigation system was to spread the agricultural development, avoiding crop failure and famine. With an area of around 16.7 Mha, Indus basin fetch around 180 BCM of water annually. On average, out of the total inflow to Indus basin, 131 BCM is diverted for various uses, 40 BCM is lost to the sea while 11 BCM are the losses per year (Bhutta & Smedema, 2007). The contiguous and trans basin Indus Basin Irrigation System (IBIS) serves as the backbone of the country. Economic growth and a huge population of Pakistan is relying on the annual inflow of the major rivers; i.e. River Indus, Ravi, Sutlej, Bias, Chenab, Jhelum river inflow to IBIS (Bhutta & Smedema, 2007).

2.1.2 Challenges for the system

This pressure-driven economy has confronted several difficulties in the last 50 years. The major sources of water to the Indus basin are water stemming from bordering countries and glacier melt in the Himalayas (Briscoe, Qamar, Contijoch, Amir, & Blackmore, 2006). Primarily the problem faced by the system is associated with the trans basin water reserves. The lines of partition cut off the inundated heartland of Punjab from the nurturing waters of the Ravi, Sutlej and Beas waterways. This issue was settled between India and Pakistan with the help of the World Bank by signing the Indus Water Treaty in 1960. The settled strategy gave Pakistan rights over the waters of Chenab, Jhelum, and Indus. These rivers make 75% of the total inflow to the entire Indus framework (Briscoe et al., 2006). Partition left the country intensely to be subordinate upon channels that are constrained by India.

In the British rule owing to an agrarian economy, irrigation was extended in the province of Punjab and Sindh. Major infrastructure development was focused on river Sutlej and Indus due to observant beneficial development along the rivers. Therefore, Punjab province used Sutlej river in its west for major water-related infrastructures. Later, separation of the sub-continent left the dependent structures, i.e. canals in the downstream i.e. in Pakistan, while the controlling structures and reservoirs in upstream India. Thus, unlike India, Pakistan does not have water from various frameworks. The geography of Pakistan made it to be entirely reliant on Indus river for water (Alam, 2002).

Subsequently, the problem faced by the Indus basin system was a jumble between the area of Pakistan's water (in the west) with the major irrigated zone in the east. To overcome this problem, the world largest dam, e.g. Tarbela dam and huge capacity link canals were made, that run miles and miles and connects the river water of western rivers to fetch irrigated lands of lower Indus basin by directing water to the part of eastern rivers in Pakistan as shown in Figure 2-1 (Briscoe et al., 2006). While previously these fallow lands were fed by the eastern rivers of Ravi, Sutlej, and Bias entirely. During his interview in 1961, Illiff (William Illiff, Vice President of the World Bank, 1956-1962) said that without channelling the water from the Indus basin, the entire country could have become a desert. The confrontation resulted in the drastic alteration of natural water regime (Bank, Archives, History, & Transcript, 1961).

2.1.3 Impact of climate constraints on Irrigation

The prevailing climatic condition in Pakistan causes agriculture in the Indus basin to be completely relying on irrigation. Such as, Pakistan's revenue-generating agrarian products are intensely reliant upon irrigated agriculture predominantly in the province of Punjab and Sindh (Alam, 2002).

There exist observant enormous occasional and yearly inconstancies even in water accessibility from irrigation; i.e. The Indus variation from 70 km^3 to 12 km^3 from summer to winter measured at the location of Kalabhag dam (Alam, 2002; Gulhati, 1973). The total of all the annual runoff diverted to the streams contributed around 84% in summer and around 36% in the winter season. Thus, the seasonal shortage of canal water diversion arises due to existent disparity between the streamflow generation and seasonal water requirement pattern (Bandaragoda & Rehman, 1995).

Watercourses of the IBIS operate on official rotational plan formed by the respective provincial irrigation department. This plan describes the time allocated to acquire water from watercourse for each farmer for their command area. Survey results suggest that current water rotational plan of Indus Basin Irrigation System is not suitable to maximize irrigation productivity with limited irrigation water (Zardari & Cordery, 2010). Reidinger (1980) said that the rotational plan of water allocation is in strife with the crop water requirement but still its extensive use occurs in various parts of the word, i.e. India, Pakistan (Bandaragoda & Rehman, 1995).

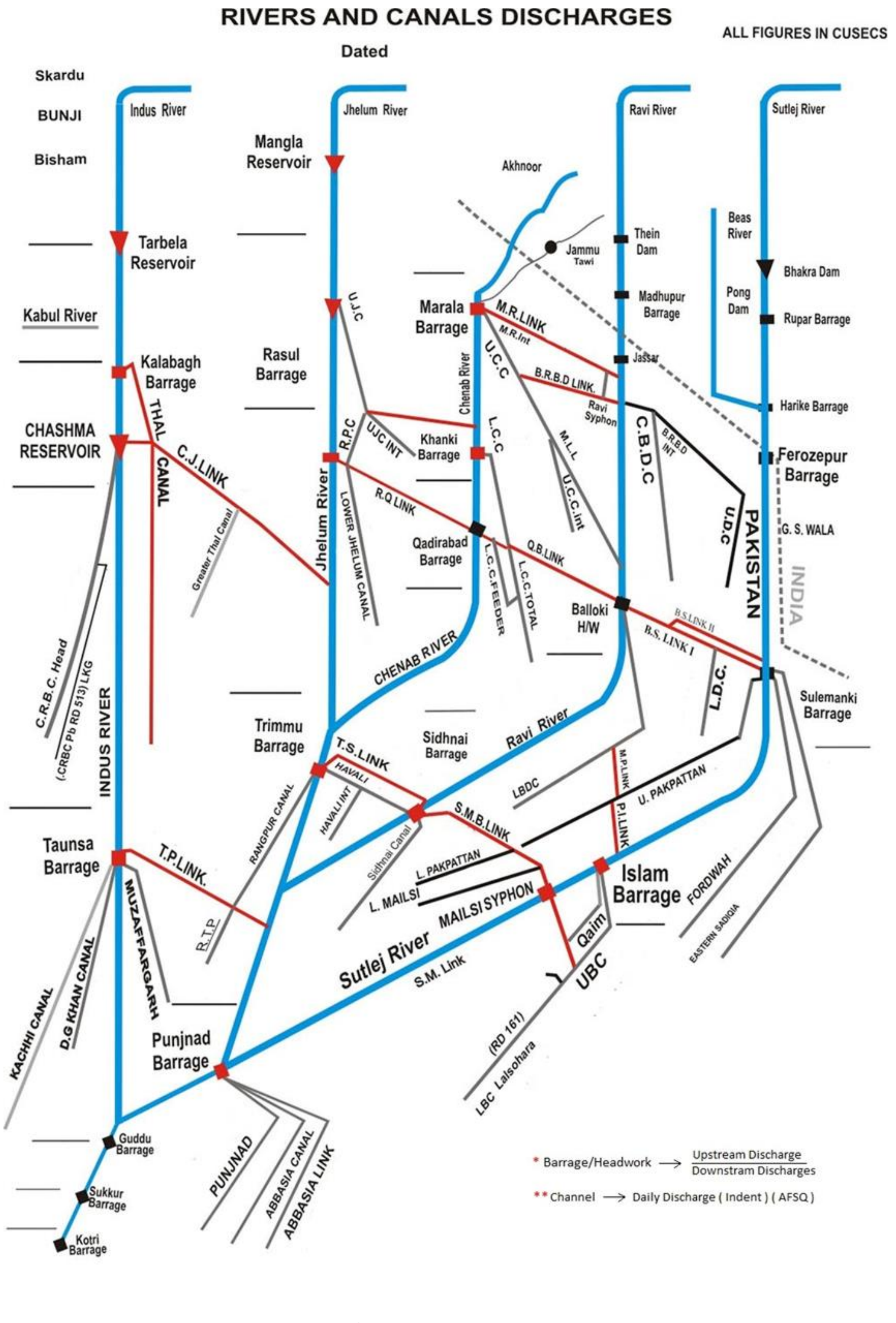


Figure 2-1 Line diagram of Pakistan irrigation system (Source: PID, Pakistan)

The intentional water deficit is further aggravated due to issues in maintenance and management, diversion and fluctuation in available water profile. The established system of water allocation has failed in delivery due to varying and unassured supplies. Disruption of service in agricultural areas with low or non-water situation affects crop yield and can create secondary salinization (Bandaragoda & Rehman, 1995).

2.1.4 Irrigation reliance on groundwater in Pakistan

Pakistan is an agricultural country that is largely relying on groundwater for its agricultural production. i.e. Indus Basin of Pakistan. Groundwater usage in Pakistan ranks 4th among all countries after India, USA, and China (Bhatti et al., 2017). Groundwater is supporting the irrigation system in Pakistan as the only source of water or coupling with canal water (Bhatti et al., 2017; Usman et al., 2015).

Groundwater requirement as an only perennial resource of water is widespread, particularly in arid and semi-arid parts of the world (Atta-Darkwa, Kyei-Baffour, Ofori, Mensah, & Agyare, 2013; Prasad, 2016; Usman et al., 2015) The overall contribution of groundwater in global freshwater requirement is around 20% (Usman et al., 2015).

Currently on average, over half of the water yield is being reimbursed by the groundwater because of its adaptable accessibility in need (Bhatti, Ahmad, Shah, & Khattak, 2018; Qureshi, McCornick, Qadir, & Aslam, 2008; Usman et al., 2015). Rice developing territories are significantly subject to groundwater use for irrigation water requirement. In these areas, around 70% of the water is extracted from the wells (Qureshi et al., 2008). Literature has confirmed the overall tremendous growth of the wells since the 1960s in Pakistan (Bhatti et al., 2018). At present, number of tube-wells has raised from 20,000 in 1960 to over one million (Bhatti et al., 2018).

Previous studies have shown elevated groundwater abstraction from 9 BCM in 1965 to 45 BCM in 2002 due to a decline in the availability of surface water. Punjab province of Pakistan is dominating in the use of groundwater and the development of private tube-wells (Bhatti et al., 2018; Nadeem, 2010; Qureshi et al., 2008). These conditions prevail especially in the southern district of Punjab; i.e. Bahawalnagar (Bhatti et al., 2018).

2.1.5 Prevailing situation and surfacing threats

Broad use of groundwater has led to a decline in the water table on a more extensive geological territory. The normal yearly drop pace of the water table in top users of groundwater, for example, Eastern India, China is 1-3 m/year (Usman, Shakoor, Ahmad, & Ahmad, 2015). A comparative situation is seen in Pakistan because of the high reliance of agriculture on groundwater (Usman et al., 2015). Different parts around the country have indicated 20% less water recharge when contrasted with the discharged measure of groundwater (Gunatilaka, 2008; Qureshi et al., 2008; Qureshi et al., 2010). Particularly the provinces of Punjab and Sindh are the top users and agriculture dominant areas in Pakistan have demonstrated an apparent decrease of groundwater table in a previous couple of years (Bhatti et al., 2017; Lang & Little, 2016).

For effective management of groundwater quantity and quality and foresee the availability, resource quantification is pre-requisite. Groundwater quantification is based on two factors; e.g. Groundwater recharge, Groundwater abstraction. (Usman et al., 2015). Groundwater recharge and abstraction shows spatial and temporal variation and hard to evaluate when the area is semi-arid or arid. Conventionally, in exclusively rainfed semi-arid and arid regions, the recharge estimation is ignored as rainfall seldom exceeds evapotranspiration or their relative difference is neglible to make any difference (Usman et al., 2015). Similar practices cannot be implemented to cases where rainfed irrigation is coupled with canal network-based artificial irrigation, which is currently prevailing in the selected study area of Pakistan.

Per capita water availability of the country has already reduced from 3000 to 1400 cubic meter per year in the time period from 1981-2010, with approximately 1.06% decrease per year. If the same declining trend continues, the per capita water availability would be reduced to less than 1000 m^3/ year, approaching the threshold of water-scarce countries (Figure 2-2).

Population explosion and reduced water availability per capita not only has given rise to groundwater usage but also has threatened the water quality particularly by increased salinity (Usman et al., 2015). In Pakistan, the data regarding the groundwater availability, abstraction, recharge, and quality, etc., is very limited and poorly produced till date despite continuous struggles made by national and international establishments (Qureshi et al., 2008; Siddiqi, 1972; Usman et al., 2015).

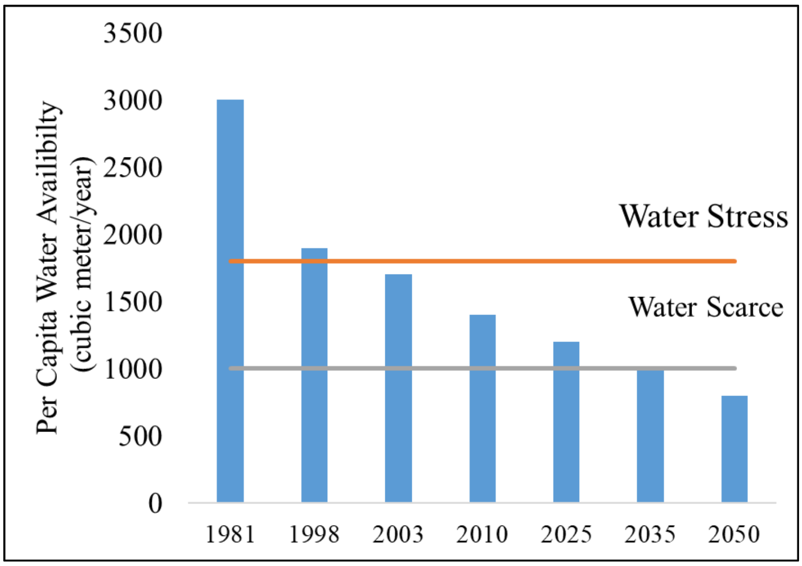


Figure 2-2 Declining per capita annual water availability in Pakistan (Source: World Bank, 2003)

High populace development and climate change are the evolving threats advancing the danger of the country to become hostile (Briscoe et al., 2006). There is uncertainty regarding future water availability in the Indus basin, with the projections based on different climate models. Existing settings depict the exacerbation of the situation in forthcoming years with population explosion, spread of irrigated lands and climate change.

2.2 Climate Change in the Light of Water Resource Management

Variability in climate has been viewed differently by various individuals. In the point of view of a typical man, climate change is an expansion in temperature and sporadic pattern of precipitation. While a meteorologist sees the environmental change in terms of increase in temperatures, both maximum and minimum, precipitation patterns and their frequency and intensity, and variation in the daylight hours. Likewise, for water in agricultural viewpoint, it is defined in terms of changing water requirements of crops, elevated rates of evapotranspiration, crop vulnerability to damage owing to waterlogging and salinization, and reduction or increase in crop yield (Akram & Hamid, 2015).

Therefore, it is suitable to think of a larger scope of indicators of climate change rather than relying only on temperature. However, every indicator under consideration would have its own association with temperature, sometimes may be very complicated. Any variable selected to describe climate change should incorporate the following criteria.

1. Continuous in time and space
2. Effectively measurable
3. Monotonically growing or decreasing
4. Should be a state variable
5. Preferably have a long record of observations
6. The regular inconstancy of the variable ought to be low

If the variable considered as representative of climate change itself naturally differs on an annual or decadal basis, the sign of existent climate change may get confused. It would be hard to evaluate whether the climate is changing. Considering, the prior criteria and availability of data, temperature performs as the best factor to depict climate change in Pakistan.

2.2.1 Vulnerability of Pakistan to climate change

Global climatic change can have additional damaging impacts on Pakistan economy. Pakistan experiences various climatic variations and thus can be classified into 4 climatic zones namely, humid, semi-arid, arid and extremely arid.

Almost ¾ of country area is lying under the arid zone and a small patch is under humid zone (Hussain & Lee, 2009; Zahid & Rasul, 2011). Thus, in areas with prevailing semi-arid and arid conditions, water is the major limiting factor for crop production.

Pakistan is divided into 10 agro-ecological zones based on climate, soil texture, land use, and physiographic characteristics (Hussain & Bangash, 2017; Kahlown, Ashraf, & Yasin, 2003; Khan, 2004). FAO (2001) has a slightly different classification consisting of 5 agro-ecological zones based on climate (Khan, 2004).

Cropland class of land use has shown a significant increase over the period. Overall increase is around 55% from 1947-1948 to 1999-2000 as reported per Agricultural Statistics of Pakistan, 1999-2000. FAO (2003) reported an increase rate of 0.3-0.4% in the land under cultivation (Khan, 2004). Best suited area for crop production lies between 33°N- 35°N latitude with the possibility of rainfed irrigation. Over and below the given scope, supplementary irrigation makes the crop production possible, most of which is in the southeastern part of the country with a low slope.

From the climatic viewpoint, Shamshad (1988), Khan et al., (2010) and Zahid et al., (2011) have divided the study area into 5 distinct seasons (Adnan, Ullah, Khan, & Gao, 2017).

1. The winter season from December to February
2. The spring season from March to April
3. Dry summer from May to June
4. The rainy monsoon season, which lasts from July to September
5. The autumn season from October to November

The monsoon season is wet, and constitutes around 44% of the yearly precipitation. For each station of the country, the average rainfall data analysis showed an overall decrease during the period from 1976 to 2005. Almost all the regions majorly from Coastal areas, West, Northeast, and North covering Zone A, Zone C and Zone E show a remarkable decrease in rainfall trend (Muhammad et al., 2017).

The temperature increase is reported as one of the index parameters for the indication of climatic change. According to the outcome of a survey conducted in Punjab province, almost 65% of farmers stated that summer temperature is increasing in Punjab. Likewise, around 26% of people noticed an increase in temperature of winters and 59% of the respondents stated that rainfalls have decreased in summer and winters.

However, few farmers (6%, 4%, and 3% for three tertiary canals) have adapted to climatic change due to temperature and rainfall for the harvesting and sowing time. Dikes are constructed at the borders of harvesting fields by only 15% of farmers in order to save water and avoid erosion. While mixed type of farming has been implemented only by 7%, 9%, and 14% at three tertiary canals, respectively (Bhatti et al., 2019).

Important input to Indus basin inflow, i.e. Snowcap of Himalayas, is also vulnerable to changes due to climate variabilities. The eastern slopes of the Himalaya mountain reach have demonstrated a critical decline in their snow spread in the course of the last couple of years. According to the reports, their snow spread has approached the most reduced value in the period of previous 10,000 years (Farooqi, Khan, & Mir, 2005).

A very recent study cautions Himalaya and Hindukush ice ranges will lose one-third to two-thirds of its ice areas by 2100. Melting of icy masses at this scale will at first result in more abundant streamflow by 2050~ 60, expanding the dangers of heavier surges, greater floods, increased soil disintegration, dam bursts and silting of water reserves, etc. While after anticipating increased streamflow period by 2050~ 60, the dry summer months, coming about in harsher dry seasons and lower yield in terms of hydropower. This will alarmingly increase the tension between bordering countries sharing water reserves (Wester, Mishra, Mukherji, Shrestha, & Change, 2019).

2.2.2 Effects of climatic change and adaptation measures

For the last few decades, special attention has been paid on climatic change due to its severe and adverse long-lasting effects on socio-economic activities, agricultural industry, health, and water resources. It is predicted that climatic change has a significantly bad impact on the agriculture industry and water resources (Bhatti et al., 2019). The agricultural industry will be adversely affected due to climatic variations without adaptation; however, appropriate adaptations can enhance the benefits and economic and social vulnerabilities can be minimized (Ficklin, Luo, Luedeling, & Zhang, 2009; Maciver & Wheaton, 2005).

Potential adaptation measures for agriculture industry may be different for different areas depending on the crops types, the effect of climatic change on economics, institutional and political conditions (Allen & Ingram, 2002; Siddiqui, Samad, Nasir, & Jalil, 2012). The global change in temperature and rainfalls potentially affected the production of crops, water resources and other agricultural components with different level of severity in different places of the world (Bhatti et al., 2019). These changes in climate are being adapted by different communities of the world in their own manners (Smit & Pilifosova, 2003). Impact of climatic change and adaptation strategies are taken into account together for assessing the climatic problem in a more realistic manner (Maciver & Wheaton, 2005).

2.2.3 Adaptation perspectives for Pakistan

The unexpected increase in temperature and considerable change in rainfall trends are expected to have an adverse impact on the socioeconomic, agriculture, and water resources. In Pakistan where livelihood is mainly agricultural-driven, climatic changes may create unfavourable circumstances if appropriate adaptations are not taken timely (Bhatti et al., 2019).

It is obvious that there is no extra water to be infused into the framework. There is no doable intervention which would empower Pakistan to prepare considerably more water than it now employs. In the present scenario, the capacity to completely and effectively use the accessible amounts is a topic of major concern.

To efficiently manage the scarce and vulnerable resource of water or to shield the existing water reserves to avert future conflicts, management is an essential input (UNESCO, Eichert, Kindler, Schultz, & Sokolov, 1982). Management follows a simple water balance approach., therefore the information regarding total water availability, its requirement and the changes in storage must be known to the manager (Ghandhari & Moghaddam, 2011). Prior to managing the resource within a basin underlying dynamics of water availability, point and type of generation of water and intended use after the treatment must be clearly understood (Bonacci, Popovska, & Geshovska, 2015).

It is subsequently vital to oversee this scarce resource well and limiting the losses. Briscoe et al., (2006) says that considerably huge amounts of water are diverted into the canal system for irrigation purposes. These diversions need to be controlled and regulated to enable a satisfactory amount of water reaching demeaning delta. Figure 2-3 is giving a clear picture of annual canal diversion and water reaches the sea.

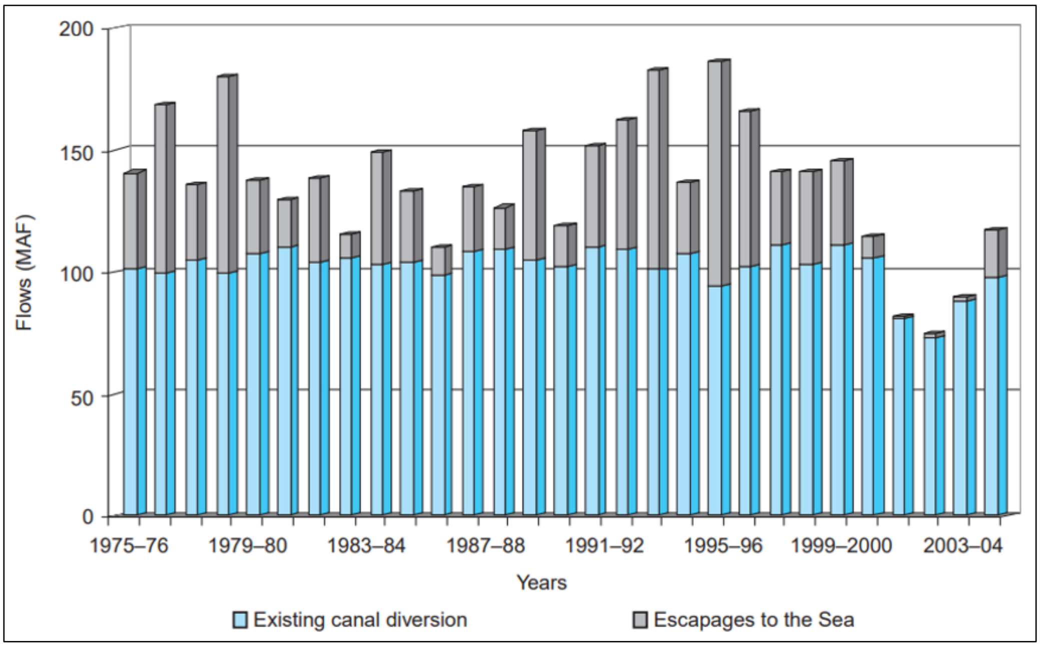


Figure 2-3 Annual amount of water diverted to canal and runoff to sea (Source: World Bank 2003)

2.2.4 Evaluating and forecasting actual requirements

In Indus basin irrigation system, the recent trend needs to be switched from predefined historic supplies of water volume to an allocation based on the actual demand (Siddiqi, Wescoat, & Muhammad, 2018). It would ensure the security of water within a channel system by forecasting an actual requirement and scheduling the deliveries.

Hence, for effective regulation of irrigation water, it is essential to model the crop water requirement. Careful allocation of water based on crop water requirement can reduce the losses ensuring a sense of security with respect to water delivery and crop yield whilst not requiring huge investment for change in infrastructure.

2.2.5 Hydrological modelling and analysis of climate variability

It is irrefutable that climate change, escalated anthropogenic activities, and their mind-boggling mutual associations have prompted huge variations in water cycles and streamflow inconstancy. Climate change directly affects the amount of precipitation and evaporation, the governing parameters for consumptive use of crops and can greatly elevate the use in future, while man-induced activities such as changes in land use, water diversion and storing structures, and other designing and management practices can alter the water distribution temporally and spatially (Wu, Mei, Chen, Hu, & Xiao, 2019).

The potential impact of climatic changes in a particular area are essential to be analyzed in order to adapt and identify the efficacy of adaptation approach reducing losses and ensuring recharge to aquifers (Ficklin et al., 2009). Secondly, there is a need to quantify the climate variabilities in the perspective area to assess the future scenario of food and water security and to ensure the optimized yield of crops. Hydrological processes are the indictors of climatic variabilities and their assessment can provide a relatively clearer picture of the future scenario.

Precipitation, temperature and stream flows are the most effective parameters for climatic change predictability especially in agriculture and water resources. Climatic changes could be forecasted using these important parameters for different regions.

Rainfall-runoff or water balance models are the simplest yet refined way to comprehend the hydrological processes and their response at a catchment level. Hence the water balance model can effectively be utilized to foresee changes in behaviour of catchment to assess results of natural as well as man-induced changes to the framework (Wu et al., 2019). Water balance model can give us clear insight into the components that are sensitive to the management within a given set of criteria (Yang et al., 2002). The model capability of finding the disparities between the estimated runoff and problems associated with assumptions can offer ease and better understanding to the modeller regarding the performance of the system, data inputs and data extraction followed by data collection and recording processes.

These well-optimized models in terms of calibration and validation can then be able to use in water resource management and climatic effect evaluation studies by simulating the rainfall-runoff response in the catchments with similar hydrological and physical features.

Water balance models demonstrate the behaviour of a natural system with the help of a water cycle using the same water balance approach. These models represent the numerical relation of precipitation to generated runoff within a catchment (Perera & Rajapakse, 2018). Relying on a clear concept and using the readily available data has made these models to be the best tools in the field of water resource management.

Utilization of hydrological models relies upon physical interpretations of the model parameters identified with the attributes of the catchment; this enables model parameters to be assessed from the catchment properties even when measured information is not accessible.

Selection and utilization of appropriate physically based models in the environmental and hydrological examination are rapidly growing. The progressive increase of issues including the forecast of future hydrologic conditions coming about because of changes in land use and climate has further put hydrological modelling into a trend (Singh & Woolhiser, 2002).

Numerous process-based distributed and physics-based lumped hydrological models are available (Onyutha, 2019). Physical process-based models are considered more sophisticated because of their detailed demonstration of the undergoing hydrological processes (Onyutha, 2019; Singh & Woolhiser, 2002)

Process-based models are preferred due to their capability and ease of adopting the available spatial datasets and real-time measurements. In a hydrological modelling environment accompanying climate and land-use changes, process-based models can perform efficient hydrologic analysis than conceptual models (Singh & Woolhiser, 2002). However, Process-based distributed models are highly data demanding and complex due to the large number of parameters involved in their structures. It is often become problematic to optimally calibrate the process-based models due to their structural complexity. Whereas, the conceptual models less complex in their structure with few governing parameters are extensively in use even at present (Onyutha, 2019; Singh & Woolhiser, 2002)

Modelling with daily time step offers more complexities and is tedious than the monthly time scale models as daily models require more detailed information as prerequisites. However, monthly models are less data-intensive and can all the more effectively and adequately be utilized to analyse the variability in the pattern of water availability on seasonal and long-term basis (Perera & Rajapakse, 2018).

The monthly time scale models have been used in various water managing and hydrological investigation studies such as drought assessment, climate change and its impact analysis on water resources, basin management through runoff simulation. At present, their application is an essential tool in the area of climate change impact, water availability and irrigation demand with seasonal and geographical variations and to access and rebuild the watershed hydrology (Mouelhi, Michel, Perrin, & Andréassian, 2006; Xu & Singh, 1998).

Using monthly resolution in a model is adequate to capture the changes within the discharge to manage the water resource and climatic variation within the catchment (Xu & Singh, 1998). Monthly resolution offers a close inter-relationship between various climatic parameters such as precipitation, temperature variations, evapotranspiration and the runoff generated from a catchment as a result of their persistent and common reaction to soil-plant-atmosphere interactions (Yen, Sharifi, Kalin, Mirhosseini, & Arnold, 2015).

Various monthly scale models have been developed and used till time. Models may vary from each other based on input data type and number of parameters they have taken into their structure to describe the numerical relationship of hydrological processes. Such as simple precipitation or rainfall and temperature or rainfall, temperature and evapotranspiration or precipitation, temperature and relative humidity as input data. Number of parameters in models may vary from simple 2~4 parameters to 10~12 parameters in complex models (Xu & Vandewiele, 1995; Xiong & Guo,

1999) i.e. Servat & Dezetter (1993) 3-parameters ‘GR3’ model, Thomas (1981) 4-parameters ‘abcd’ model, Abulohom et al., (2001) 5-parameters model, Xu (2000) 6-parameters model ,Servat & Dezetter (1993), ‘CREC’ model based on 7-parameters, Hughes & Metzler (2010) 12-parameters ‘Pitman’ water balance model.

2.2.6 Selection of the ‘*abcdm*’ model

Modelling of an ungauged or poorly gauged catchment under the data-scarce situation has consistently been a problem. Out of numerous watershed models, the four-parameter ‘*abcd*’ and two-parameter lumped models are more broadly utilized in hydrologic related investigations because of their capability to sensibly screen the response of a catchment (Perera & Rajapakse, 2018).

Two parameter model is appropriate to use in estimating the surface runoff and flood modelling studies, while the studies where the contribution of groundwater component is considered limits the use of two-parameter model as two parameters cannot incorporate the groundwater inherently. In such situations, four parameters ‘abcd’ model can effectively be used (Perera & Rajapakse, 2018).

2.2.7 Model components

The ‘abcd’ model basically having four parameters (*a*, *b*, *c*, *d*) is a monthly hydrological model created by Thomas Jr. in 1981 (Martinez & Gupta, 2010a). The model requires precipitation and potential evapotranspiration as input data, that further utilized to estimate the actual evapotranspiration, changes in groundwater storage and subsequently appearing surface/subsurface flows. The ‘*abcd*’ model is well recognized for hydro-climatological studies and has performed well in an arid and sub-humid climate (Wang et al., 2011).

The ‘*abcd*’ model in its original form has limited applicability for snow dominant areas as in such areas, snowmelt can significantly contribute to the runoff thus affecting the model efficiency and hence reliability. To overcome the inherent inadequacy of the primary model, snowmelt module is incorporated within the structure of the primary model (Xu et al., 1996; Martinez & Gupta, 2010b).

It utilizes a factor '*m*' relative to the snowmelt contribution to represent the snow module that can depict three phenomena; i.e. snowfall, snow storage/ cover, and snowmelt. Basically, the temperature variations are utilized to separate the snowfall from the water that falls as a liquid; i.e. rainfall and later it is used to estimate the contribution from snowmelt in terms of snow water equivalent. Figure 2-4 is describing the conceptual interpretation of the '*abcdm*' model with incorporated snow module (Wu et al., 2019).

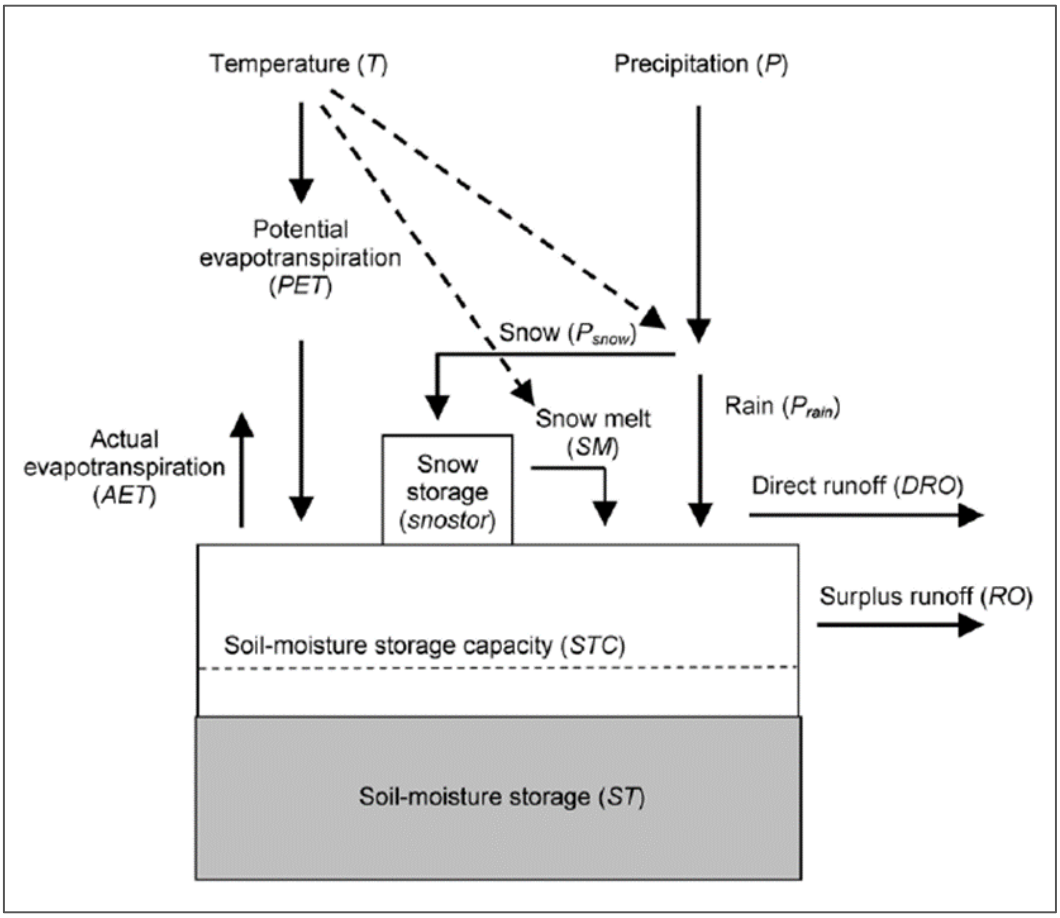


Figure 2-4 Conceptual interpretation of water balance approach

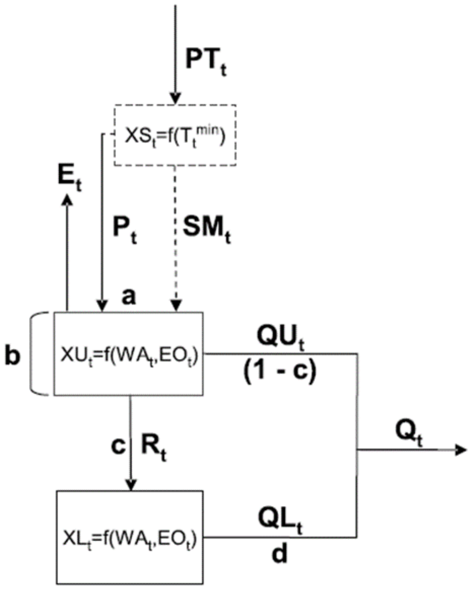


Figure 2-5 Conceptual diagram of the ‘abcdm’ model

2.2.8 Model evaluation criteria

The process of predicting realistic values of the governing model parameters so that simulation results can match with observations is known as calibration. because The problems associated to data availability, initial conditions, boundary conditions and model structure can significantly risk the model output therefore, calibration of a hydrological model is required to produce reliable results(Kumarasamy & Belmont, 2018).

Rainfall-runoff modelling always offers a challenge to the modeller while ensuring the accuracy of the simulated flows comparative to the already observed flows. It is difficult but crucial to simulate the model to the extent where it can respond accurately to the low and high flows in a single calibration. The underlying cause may be the structure of the models that are designed to capture the high flows in a sounder way while comparing to capturing the low flows.

Moriasi et al., (2007) state that there are various model evaluation techniques which can be broadly classified as statistical and graphical. They recommend quantitative statistics, Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and the ratio of the root mean square error to the standard deviation of measured data (RSR), in addition to the graphical techniques, to be used for evaluation of any model.

The Kling-Gupta Efficiency (KGE) is also used as an objective function to calibrate and validate the constructed model. The KGE is an improved form of Nash-Sutcliffe Efficiency (NSE). The KGE takes three free factual criteria into account and fits in one multi-objective criteria; i.e. linearity between the simulated and observed flows (γ), Bias ration (β) and relative variability (α) given in equation (1). Bias ratio is the ratio of the averages of simulated and observed flow, while Relative variability is given as the ratio of the standard deviation of simulated and observed flows respectively. The KGE overweighs the application of NSE as an objective function by avoiding overemphasizes on the match of high streams (Bai et al., 2018), and is defined as;

$$KGE = 1 - \sqrt{(1-\gamma)^2 + (1-\alpha)^2 + (1-\beta)^2} \qquad \text{(Eq.1)}$$

where,

β = Ratio of the mean values of simulated flows and observed flows respectively,
α =Ratio of the Standard deviations of simulated and observed flows, respectively, and
γ = Pearson Correlation coefficient between the simulated and observed flows.

The KGE objective function in overall describes the comprehensive assessment of the model for the undertaken study. It is used to evaluate the agreement between the simulated and observed record of discharge data for the catchment.

Other criteria considered for model evaluation are per cent bias (PBIAS) and coefficient of determination (R^2) as given by Equations (2) and (3). The R^2 describes the capability of a model to explain the variabilities in observed data through simulation, while percent bias describes the normal inclination of the simulated values to be different from the mean observed values.

The optimum values for KGE, R^2, and PBIAS are 1, 1, and 0, respectively. The R^2 and PBIAS are defined as;

$$R^2 = \frac{\sum\left((q_{obs} - \bar{q}_{obs})(q_{sim} - \bar{q}_{sim})\right)^2}{\sqrt{(q_{obs} - \bar{q}_{obs})^2 (q_{sim} - \bar{q}_{sim})^2}} \qquad \text{(Eq.2)}$$

$$PBIAS = \frac{\sum_{i=1}^{n}(q_{obs} - q_{sim}) * 100}{\sum_{i=1}^{n} q_{obs}} \qquad \text{(Eq.3)}$$

where,

q_{obs} = Observed flow,

q_{sim} = Modelled/ Simulated flow,

$\bar{q}_{sim}$= Average Simulated flow $\bar{q}$, and

$\bar{q}_{obs}$= Average observed flow.

Wijesekera and Perera (2012) used the MRAE objective function for finalizing the parameters of the model with minimum MRAE values. Author further states that along with having an objective function, it is important to assess parameters using visual comparisons, numerical indicators, water balance, and flow duration curves to obtain realistic parameters.

Modelling of irrigation requirement based on current irrigated area, climatic parameters and cropping pattern provides basics to quantify the impacts of climatic variations and other socioeconomic, technical and demographic changes (Shangguan et al., 2002).

2.2.9 Advancements in decision control systems

Other options under consideration to diminish the wastages for future water security includes the advancement of the decision support and control systems. Irrigation channels draw an extended thought in this regard (Ooi et al., 2005; Reddy, 1991).

An article in the Journal of Irrigation and Drainage Engineering in 1998 highlighted on canal automation along with the Conference on Man and Artificial Intelligence

(1998). In the proceedings of the conference, IEEE Frameworks exclusively presented the modelling and regulation of water in irrigation channels (Ooi et al., 2005).

In other words, it urges the need to revolutionize the established unorganized water allocation to a demand-based system combined with managing recharge to the aquifers within the riverine system to make Pakistan secure for events of conceivable dry spells.

2.2.10 Numerical modelling of channel flow

Irrigation canals, unlike river systems, are composite hydraulic systems and problematic to control. Irrigation canal modelling, like river systems, is based on unsteady flow equation but the modelling environment undergoes various problems due to non-uniform varying conditions.

Previously, system identification methods were in use to model the flows within an irrigation channel network. These models use the prediction error method to process the operational data obtained from the field (Brunner, Warner, Wolfe, Piper, & Marston, 2016; Ooi et al., 2005; Salahou, 2013).

The commonly occurring structures in an irrigation network, weirs, gates, etc., are of non-linear nature. Thus, the analytical models can not provide a solution for complete irrigation channels and there is a need to have an advanced numerical method (Salahou, 2013).

Conventionally, the dynamics of the open channels are modelled by the St. Venant equations (Brunner et al., 2016; Jr & Merkley, 1994; Ooi et al., 2005; Salahou, 2013; UNESCO et al., 1982). Saint-Venant equations derived from mass and momentum balance equations best describe the unsteady flow in one dimension in an open channel flow under gravity. Saint-Venant Equation is best to use while operational data is not available, and it also tells the water level at the intermediate point within the channel while the system identification methods can only modal the flows at the downstream (Islam, Raghuwanshi, & Singh, 2008; Jr & Merkley, 1994).

Numerical solution of Saint-Venant equation can be obtained by various methods, namely finite difference method, finite element method, and method of characteristics, etc. From literature, the extensively used method to estimate the numerical solution to the Saint-Venant equation is the finite difference method. The most common practice is to use the Preissmann scheme based on finite difference method (Hirsch, Gotway, & Helsel, 2002; Islam et al., 2008; Khanna & Malano, 2006; Ooi et al., 2005).

Accuracy of the Saint-Venant equation is accessed by validating the simulated flows achieved from Preissmann scheme against the measured water level (Ooi et al., 2005).

The HEC-RAS model developed by the U.S. Army Corps of Engineering´s Hydrologic Engineering Centre is a hydraulic analysis tool of the river system. Basic input requirement of the hydraulic model is geometric data and channel flows. Basic geometry includes physical features of the river system; i.e. channel length, bank of the channel, flood paths and cross-sections while other geometric data defining inline structures, storage areas, etc. can also be incorporated using the software. One-dimensional and two-dimensional calculations can be performed using HEC-RAS Model. Taking into consideration the unsteady flow conditions within the channel, 1D or 2D simulation can be performed to simulate flow and computing water surface profile (Brunner et al., 2016).

For the undertaken study, HEC-RAS 1-D model has been recommended for the simulation and analysis of unsteady, gradually varied flow (GVF) in an earthen constructed channel and its hydraulic characteristics. The solution of unsteady GVF is governed by the Famous Saint-Venant equation (Eq. 4,5). The governing equations of the model are;

$$\frac{\partial \mathrm{Q}}{\partial \mathrm{x}} + \frac{\partial A}{\partial t} = 0 \qquad \text{(Eq.4)}$$

$$\left(\frac{\partial Q}{\partial t} + \frac{\partial \left(\frac{\alpha Q^2}{A} \right)}{\partial x} + gA \left(\frac{\partial h}{\partial x} - S_o + S_f \right) \right) = 0 \qquad \text{(Eq.5)}$$

where,

Q = Flow through the channel,

A = Area of x-section carrying discharge,

y = Depth of flow,

S_o= Channel bottom slope, and

S_f = Friction slope.

The function of HEC-RAS is to provide the water surface elevation at various points of interest along the channel.

3 METHODOLOGY AND MATERIALS

3.1 Methodology Brief

Study area i.e. Hakra canal command area (part of IBIS) has been selected as it is predominantly an agricultural area thus can best describe the irrigation water situation in the country. It is also representative of the climatic conditions of the Punjab province. Any anomalies in the sustainability of this system can have wide ranging effects on the economy of the country as millions of people are dependent on the agricultural sector. Impact of climate over the water scarcity is an important issue to be studied. Water scarcity is no more a regional problem and its global extent has put it in scope for future research. The output of the research work can assist in ongoing poverty alleviation drives.

After assessing the criticalness of problem and literature survey, data requirements for carrying out the research is evaluated. Data is analysed and processed for identifying any discrepancies and shortcoming prior to their usage in the study. Based on long-term climate data, actual requirements of water for crop consumptive use are evaluated and a comparison is made with the actual availability of water delivered by Punjab Irrigation Department in compatible units. The deficit between the demand and availability is estimated in terms of groundwater contribution and results are verified with the monitored depth of the groundwater table in a qualitative manner for the study period from 2010 ~ 2017. Climatic variability being the important factor linked to crop consumptive use and irrigation requirement, it is assessed for the area and results are verified analysing the change in hydrological processes such as streamflow generation with the help of hydrological modelling.

3.2 Methodology Flowchart

Detailed schematic of the methodological steps adopted for the following study is illustrated in Figure 3-1. Figure 3-2 is illustrating the methodological steps for the selection of the hydrological model and process of hydrological modelling.

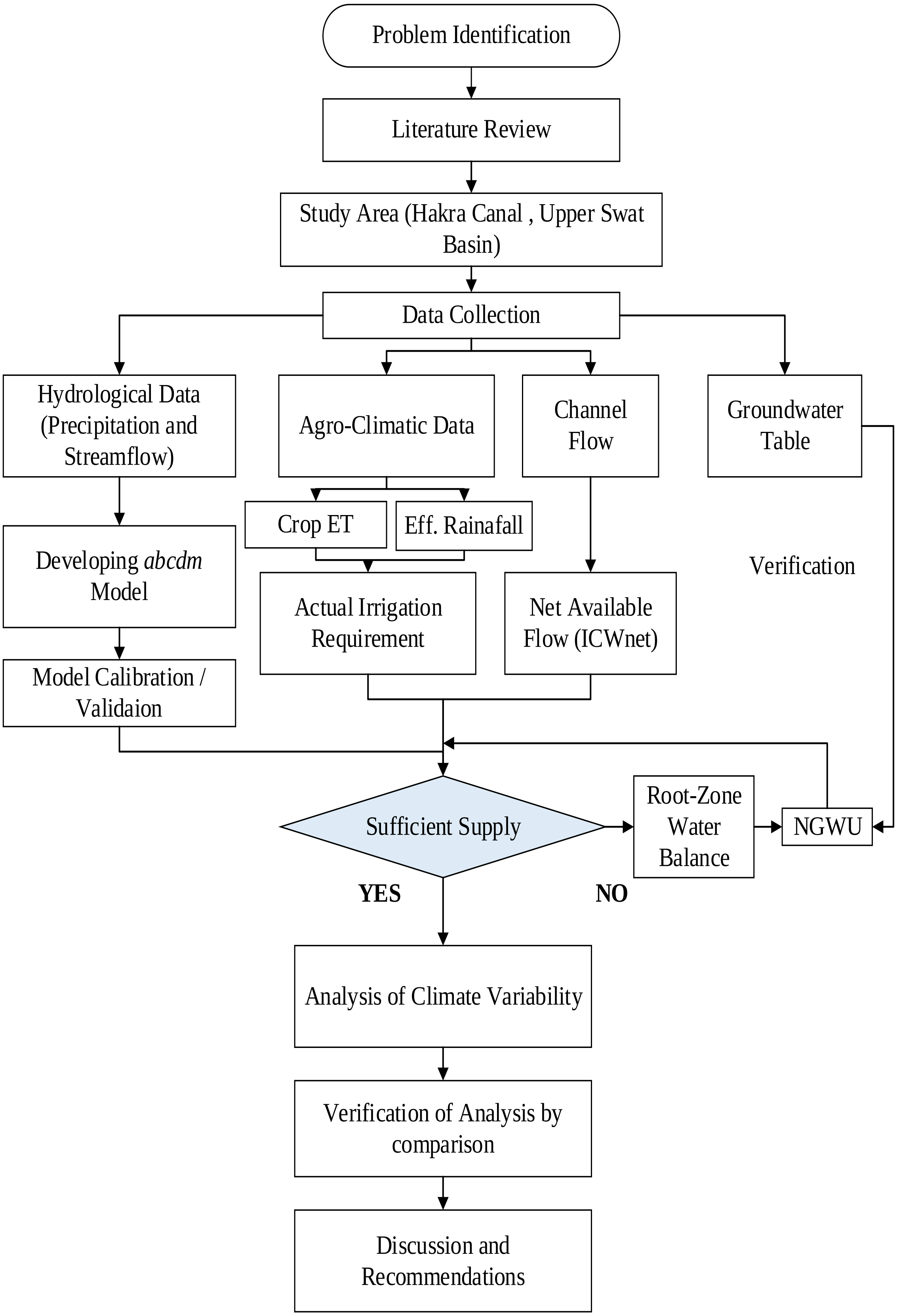


Figure 3-1 Methodology flowchart of the study

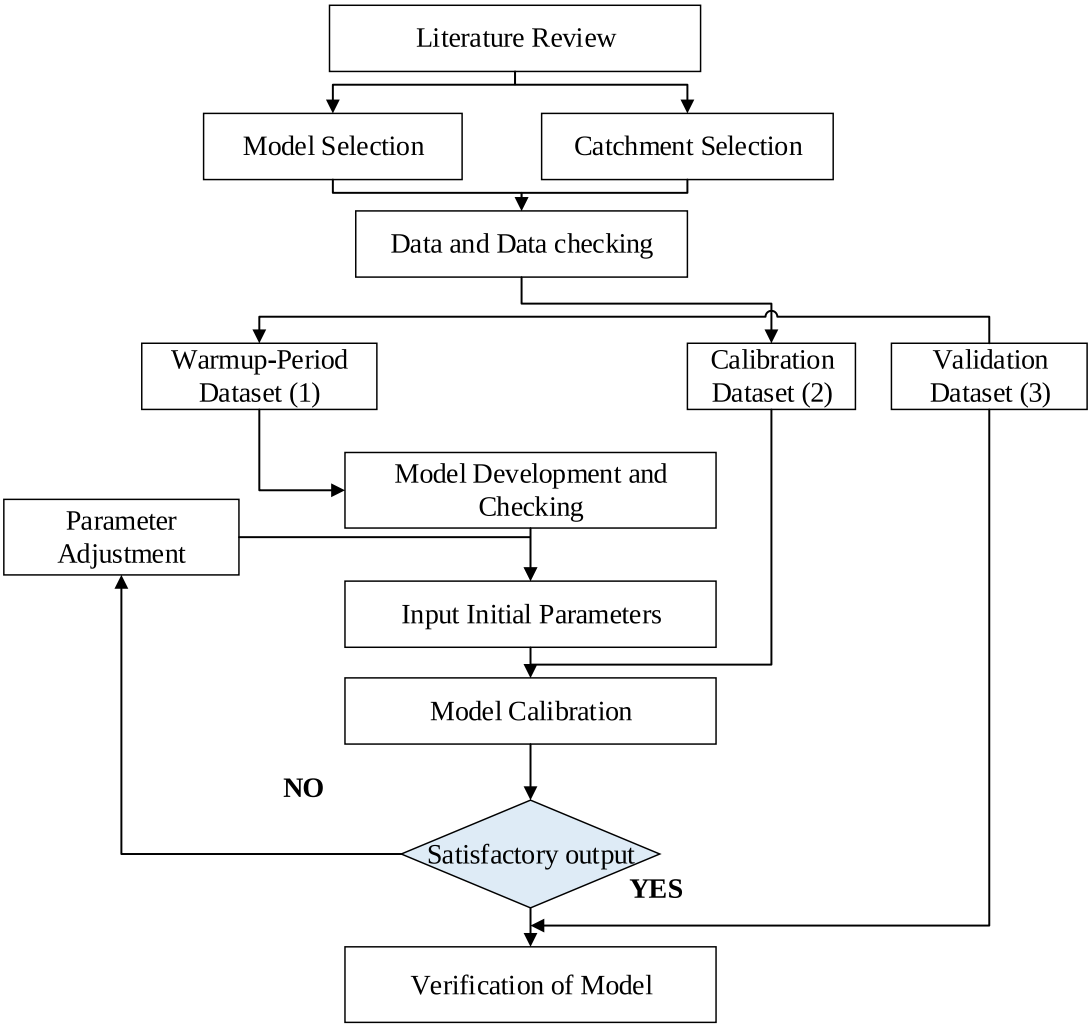


Figure 3-2 Selection of model and hydrological modelling

3.3 Introduction to Study Area

The Study reach (Hakra Canal) (Figure 3-3) is located between latitude 29° 55' N and 29° 14' N and longitude 73° 22' E and 73° 3' E. Hakra canal lying in Bahawalnagar district of the south-eastern region of Punjab, Pakistan, is approximately 92 km long and covers about 2,031 km^2 of the land. The study area is predominately an agricultural area with a dry climate and follows wheat-cotton cropping pattern.

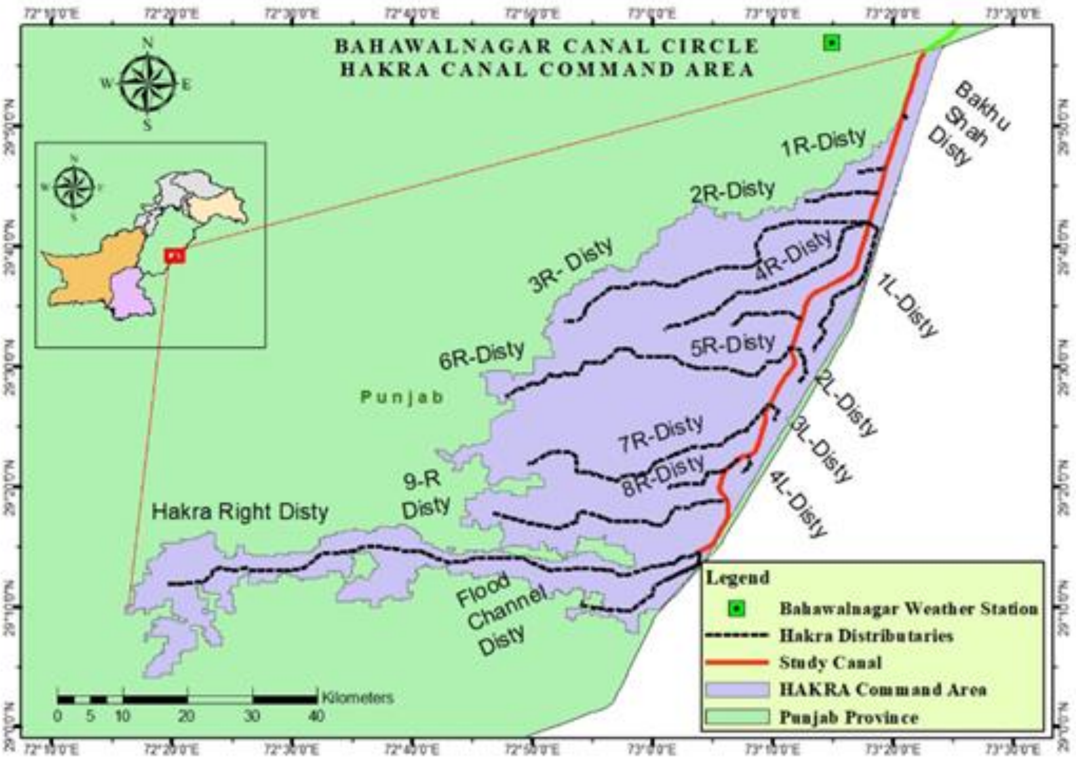


Figure 3-3 Hakra canal command area, Punjab, Pakistan

Hakra canal is a secondary canal with an average discharge of 2.33 m^3/s. It originates from the main Eastern Sadiqia canal when the latter trifurcates at Jalawala headworks after running around 74 km from its origin. Detailed schematic of the canal is given in (Figure 3-4).

From the climatic viewpoint, the study area undergoes five distinct temperature seasons such as

1. The winter season from December to February
2. The spring season from March to April
3. Dry summer from May to June
4. The rainy monsoon season, which lasts from July to September
5. The autumn season from October to November

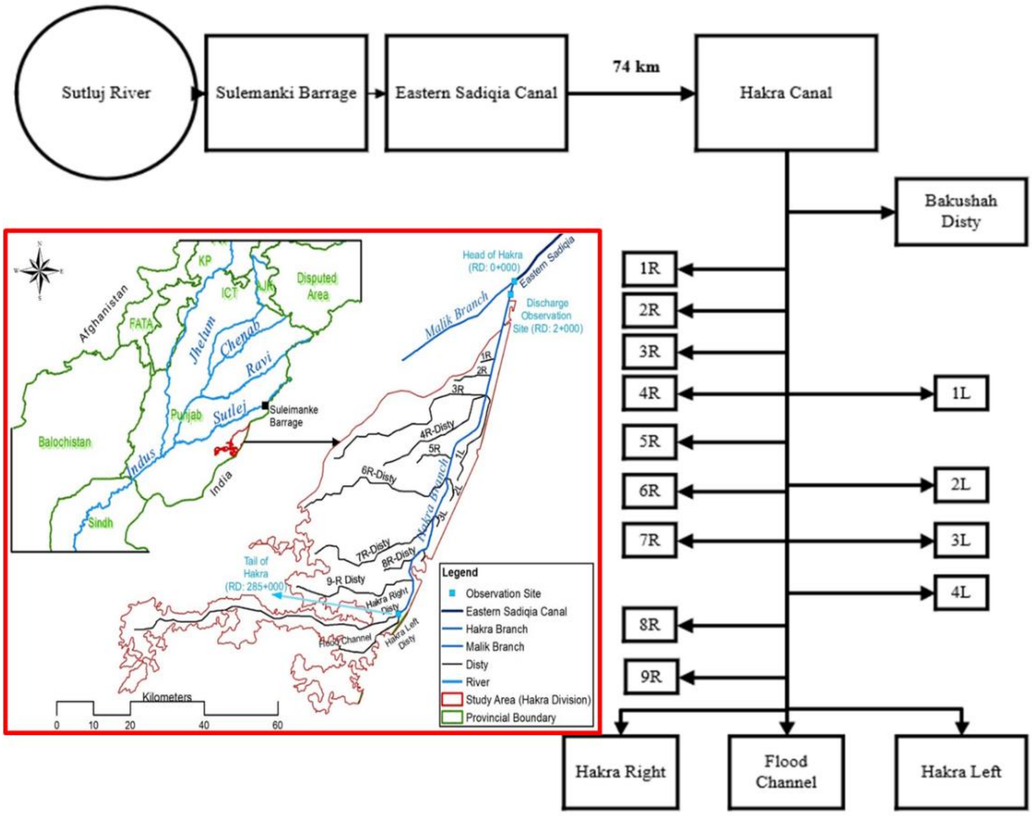


Figure 3-4 Schematic diagram of the Hakra canal command area

Based on climatic characterization, the study area is classified as a semi-arid zone with a mean annual rainfall of 150 mm, compared to mean annual reference evapotranspiration of around 1678 mm (Qureshi et al., 2010). The rainy season usually occurs between July to September (Khan, 2004). The minimum temperature is observed from December to February and maximum from May to August. June is recorded as the month of highest temperature with a mean temperature of 42.2°C and December as the month of lowest temperature. The relative humidity is higher in the month of January and the average humidity is 57.4% (Adnan, Ullah, Khan, & Gao, 2017). Study area taken under consideration is imperative owing to a representative of climatic conditions of the Punjab province. Any inconsistencies in this framework can have wide extending impacts on the economy of the territory, particularly on the ongoing poverty alleviation drives, as millions of individuals are dependent on the agri-food sector. Additionally, it flows a few meters away from the Indian border and considered as the major landmark of defence against any opponent intrusion.

3.4 Data and Data Collection

A better understanding of the meteorological, hydrologic and topographical conditions of the study area helps to investigate and imitate the actual hydraulic situation. Dataset defining those parameters is obtained from various resources. The obtained dataset had deficiency owing to various reasons and need to be screened and processed before using them as the quality of the data have a direct impact on the modeling output.

3.4.1 Meteorological data

There is one meteorological station within the study area and real-time data of all climatic factor is available for the period of 2010-2017. Meteorological data include rainfall, sunshine hours, humidity, wind speed, and temperature data. All climatological data for the Hakra canal is collected for Punjab Meteorological Department.

3.4.2 Hydrological data

For the verification of climate change variability of the study area, the streamflow data for the Kalam station in the verification basin for the duration of 1961~2012 is collected.

3.4.3 Soil cover

Soil texture map of Bahawalnagar district was attained from Directorate of Soil Fertility Research Institute in Punjab, Lahore. It represents the five (5) basic soil classification as Sand, Sandy loam, Loam, Clay loam, and Clay. The major percentage of the study area consisted of loam while the rest of the area is composed of sandy loam.

3.4.4 Land cover map

Land cover map of the study area as a GIS layer is collected from the Irrigation Department, Punjab, Pakistan. Land cover in Hakra canal basin has been classified into three categories as Cropland, Permanent or seasonal water bodies, Urban or Bare land. Cultivated land is a dominant land type whereas waterbodies are least present.

3.4.5 Digital elevation model

For identifying the topographical features of the study area, 30 m spatial resolution DEM (Digital Elevation Model) was downloaded from STRM - Shuttle Radar Topography Mission, an open source/public domain resource maintained by USGS/NASA (USA). Details of the acquired dataset are given in Table 3-1.

Table 3-1 Data source and description

Data Type	Data Resolution	Duration	Data Source
DEM	30 m x 30 m	---	Shuttle Radar Topography Mission (SRTM)
Land use	30 m x 30 m	---	Irrigation Department, Punjab, Pakistan.
Soil	1:1,000,000	---	Directorate of Soil Fertility Research Institute Punjab Lahore.
Climate	Daily Monthly	2008 ~2017 1978 ~2017	Punjab Meteorological Department.
Canal Discharge	Daily	2010 ~2017	Irrigation Department, Punjab, Pakistan.
Cropping Pattern	Seasonal (Rabi, Kharif)	2010 ~2017	Pakistan Bureau of Statistics, Pakistan Agricultural Research Council
Groundwater Table	Twice a year	2010 ~2017	Salinity Monitoring Organization (SMO), WAPDA, Pakistan
Kalam Runoff	Monthly	1961~2012	Irrigation Department, Punjab, Pakistan

3.5 Data Checking and Treatment

Loss of information or discrepancies in the data i.e. Meteorological data, required for quantitative research is no more exception. Loss of information may involve various reasons; i.e. rough climatic conditions, instrumental faults, and failure or personal error amid information handling and recording (Suhaila, Deni, & Jemain, 2008; Wan Ismail, Wan, & Wan Ibrahim, 2017).

Characteristics of the missing data are crucial to be analysed before applying any missing data treatment method. These characteristics include fraction or rate by which data is missing, non-response pattern and non-response mechanism.

Pattern by which data is missing and possible mechanism overweighs the proportion of discrepancies in the data (Tabachnick & Fidell, 2013). Thus, a researcher needs to analyse all three aspects; i.e. Percentage of missing data, Nonresponse mechanism, and Nonresponse pattern.

3.5.1 Analysis of missing data

Literature does not seem to provide any established standard with respect to acceptable rate of missing data in an information set for substantial measurable deductions (Dong & Peng, 2013). For instance, Schafer (1999), said that 5% or less rate of missing data is insignificant. According to Bennett (2001), if the missing rate exceeding 10% it can cause biases in statistical analysis. Ender (2003) reported that the rate of missing data was around 15~20% based on the previously published educational and psychological researches.

Obtained monthly dataset of rainfall for Bahawalnagar meteorological station from 1978 to 2017 is assessed for the percentage of missing data. Figure 3-5 is showing the summary of the analysis of missing data by classifying it into three classes; i.e. Missing by variables, missing by cases and missing by values. With respect to the number of missing values, around 5.5% data is missing. As the percentage of missing data is more than 5%, thus dropping the record would have caused significant data loss.

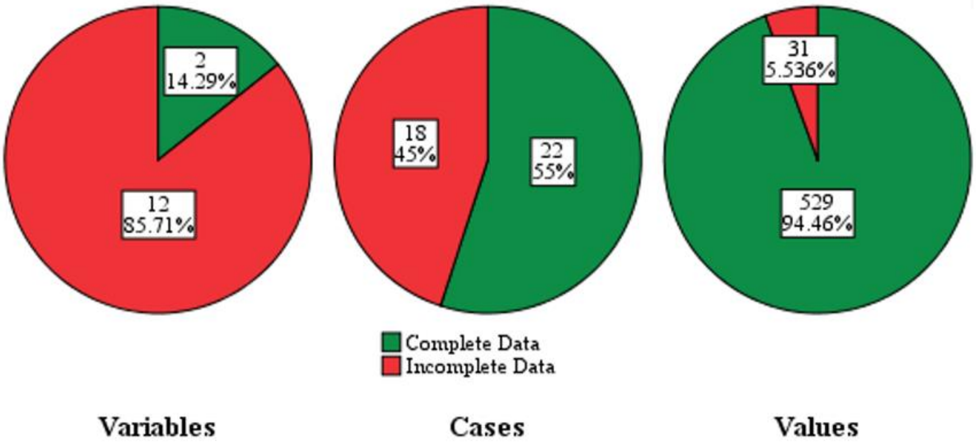


Figure 3-5 Summary of missing values in dataset

Considering the significant level of missing data and deciding about the appropriate treatment method, pattern and mechanism of missingness for the acquired dataset also need to be inspected. Non-response patterns classified as univariate, monotone and arbitrary pattern. Non-response mechanism depicts the relationship of the missing data with missingness. Based on the interrelationship there are three classes of missing mechanism i.e. Missing at random (MAR) which highlights the missingness of data with the observed values in a systematic manner, missing completely at random (MCAR) tells that the missing data is completely independent of the observed and missing dataset and missing not at random (MNAR) mechanism specify that the missingness is an attribute of both missing and observed dataset (Lang & Little, 2016).

The Missing data completely at random type of data is most easy to deal with and simple treatment methods such as pairwise or listwise deletion can be utilized. Convenience to deal with missingness of MCAR data is followed by MAR. While MNAR type data is most hard to treat.

Statistical Package for Social Sciences (SPSS) is used to analyse the randomness of missing data as shown in Figure 3-6. Apparently, the obtained rainfall data had missing values at random therefore the possibility of MNAR mechanisms of missingness is rejected. Missing values in a complete dataset are classified into 17 different patterns and variables are the months in which missing data is observed. Pattern numbered as 14 seemed to be most populated.

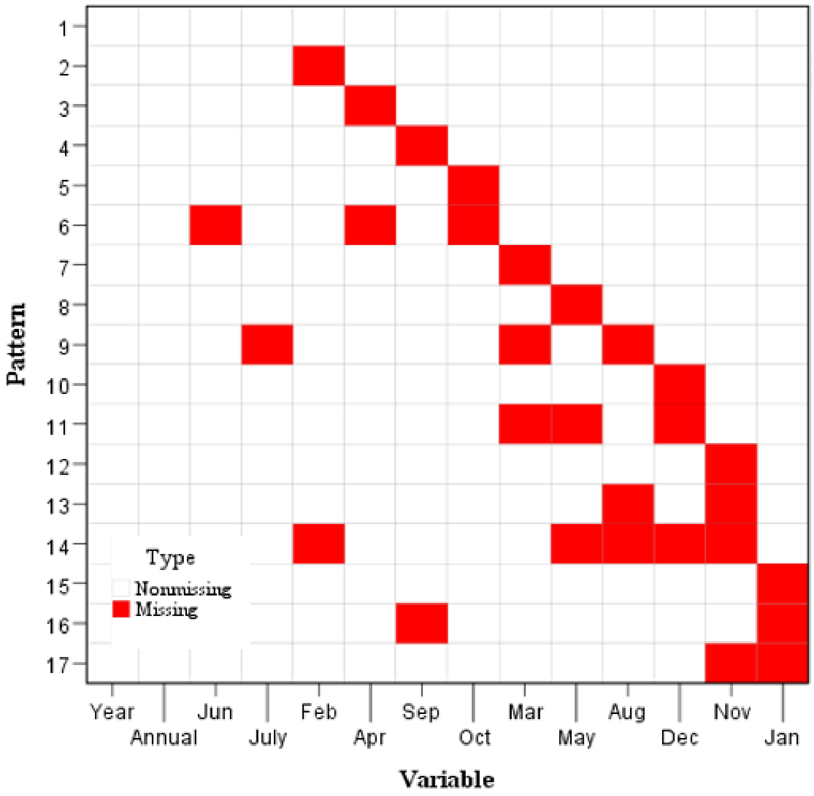


Figure 3-6 Visual analysis of data for observing missing patterns

For a completely missing at random data, the values must follow a staircase shape pattern that is not observed for the tested dataset in Figure 3-6. Mathematically, the MCAR can be checked using the Student t-test. Little and Schenker (1995) stated that the MCAR mechanism of missing data can be assessed by the Little’s multivariate test.

To evaluate the Missing completely at random (MCAR) pattern of obtained data, widely accepted t-test is performed. For that purpose, whole data is divided into two sets; i.e. complete data and data with missing values. The t-test, mean difference method results are used to access the difference between two formulated datasets.

Later, the Little’s MCAR test was also carried out using the Statistical Package for Social Sciences (SPSS) to confirm the results (Table 3-2). For that, null hypothesis was made that data is missing at completely random with the alternate hypothesis stating that data is not missing completely at random.

Table 3-2 Little's missing completely at random for missing pattern analysis

EM Means[a]											
Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
11.70	18.00	18.38	12.52	13.14	36.438	73.37	43.02	32.31	6.56	3.18	3.00
a. Little's MCAR test: Chi-Square = 201.592, DF = 163, Sig. =0.021											

The significance of the MCAR test came out as 0.021 < 0.05 (5% significance level) which means it is non-significant, thus we rejected the null hypothesis that data is Missing Completely at Random (MCAR) and probably had some certain missing pattern. There was some sort of systematic biasness in the data. Results of the test helped us to select a suitable technique for the replacement of missing data.

3.5.2 Treatment of missing data

Missing data if not handled cautiously and precisely, can severely damage the research's inferences and can even weaken the generalizability (Lang & Little, 2016; Little, 1992; Little & Rubin, 1989). Methods to estimate missing hydrological data based on literature are classified as Single value approach, i.e. Regression analysis, Linear interpolation, etc., and Group approach (Elshorbagy, Panu, & Simonovic, 2000). The current study is based on the estimation of missing data through single value approach as it is the most commonly used approach. Group approach is gaining popularity with the passage of time but has been used in a few studies till the time.

Deletion-based techniques remained the most common technique to treat the missing data. Among studies that showed evidence of missing data, 97% used the listwise deletion (LD) or the pairwise deletion (PD) method to deal with missing data (Dong & Peng, 2013). Both listwise and pairwise deletion methods are ad hoc in nature and produced biased results in most of the situations. Therefore, use of these methods is highly decried by the theorist (Dong & Peng, 2013; Little, 1992; Little & Rubin, 1989).

For the estimation of meteorological or hydrological data, the arithmetic mean method is the simplest method available. For the obtained meteorological data, the average annual precipitation of index stations does not lie within 10% of the normal annual precipitation of the suspect station, and that limits the use of arithmetic mean method for data filling. It indicated the presence of huge variation among the annual rainfall of neighbouring stations.

Another commonly used method of treating missing rainfall data is by infilling method; i.e. Closest station method with monthly time scale showed very good performance at Andes region of Venezuela (Garcia, Sentelhas, Tapia, & Sparovek, 2006). For the concerned metrological station, i.e. Bahawalnagar station, the acquired dataset of nearby stations was also having the missing entities. Consequently, to be more precise regarding data treatment, this choice of treatment using the closest station method was declined.

Recent researches are more focused on the use of newer techniques such as Expectation maximization, Multiple imputations and Full information maximum likelihood (FIML), etc., for data filling rather than removing data using LD and PD. These methods are likely to estimate the missing values using an observed dataset with some statistical assumptions rather than direct interpretation. These techniques are believed to provide more reliable estimates due to taking into consideration the conditions under which the discrepancies arose (Dong & Peng, 2013; Little, 1992; Little & Rubin, 1989). An appropriate application of these methods can ensure the validity of study even in case of prolonged nonresponse (Lang & Little, 2016). The suitability of a method may vary based on the situation and type of data.

The literature highlighted several other methods and models to serve the purpose; i.e. Time series analysis, Regression analysis, Interpolation, Probabilistic method, Artificial neural network (ANN), etc. (Wan Ismail et al., 2017). Various methods to treat the missing data are summarized in the Table A-2.1 in Appendix-A.

For the acquired dataset, The data is not following MCAR, and the simple data deletion techniques such as deletion listwise or pairwise could not be used. Thus, there is need to impute the values to replace missing data in order to avoid inaccurate inferences from data. Therefore, an appropriate data filling approach of multiple imputations using the literature support and statistical analysis of data with missing values is carried out. Replacing missing data by multiple imputations is a tedious and complicated job. For the sake of easiness and to overcome any personal error, Statistical Package for Social Sciences (SPSS) is utilized. The missing values are imputed using SPSS using Multiple imputation command. Imputation is based on the regression model.

3.5.3 Analysis of normality of data

The parameter of concern may vary from the mean value on the course of time due to many natural or anthropogenic reasons (IAHS/WMO, 1974). Several situations can also produce variation in the measured climatological and hydrological variables. These changes may follow linear or non- linear trend along the time series.

There are various models, i.e. linear & non-linear, available to analyse and express the trend within the given data series. Linear models are more common in the field of the hydrology (Helsel & Hirsch, 2002). Selection of the model depends on the characteristics of the available data set. Therefore, a completed dataset of meteorological or hydrological data must be assessed for normality and consistency. The purpose is to check the stationarity in dataset both on temporal and spatial scales.

Normality test tells either the data is symmetrical and following a bell-shaped curve or unsymmetrical and skewed. Normality of the data must be assessed prior to the analysis of the trend. Normality of the data can be assessed using various tests discussed in the literature, i.e. “Kolmogorov-Smirnov (K-S) Test, Lilliefors corrected K-S test, Anderson-Darling test, Shapiro-Wilk test”, etc. Among all the normality tests, K-S test is the most commonly used option (Ghasemi & Zahediasl, 2012).

To analyse the normal distribution of data, Kolmogorov-Smirnov (K-S) test of normality is manually performed assuming a null hypothesis of the normal distribution with an alternate hypothesis of non-normal distribution. For a normal set of data critical value of K-S statistic must be greater than the observed K-S value. Critical value for a sample size of 40 data points (1978 ~ 2017) obtained from the table of K-S test statistics is 0.218 at 95% confidence level, while the value of K-S statistics obtained for the data is 0.101. The value of the K-S test is less than the critical value. Accordingly, we can conclude that data is following the normal distribution as we failed to reject the null hypothesis.

The results of normality analysis of data are further re-evaluated by SPSS using mathematical and graphical approaches namely descriptive analysis, Kolmogorov-Smirnov (K-S) Lilliefors correction test, Shapiro Wilk test and normal Q-Q plot. The results of the normality tests performed using SPSS are presented in the Table 3-3, 3-4 and 3-5.

Table 3-3 Normality analysis of data using SPSS

Kolmogorov-Smirnov Lilliefors Correction Test			**Shapiro-Wilk Test**		
Statistic	D_f	P-value	Statistic	D_f	P-value
0.094	40	0.200*	0.954	40	0.102
* This is a lower bound of the true significance.					

Results of Kolmogorov-Smirnov Lilliefors Correction Test that is an improved form of K-S test and Shapiro-Wilk Test are reconfirming the previously obtained results of normality. As in the case of both tests, the P-value is greater than 5% significance (0.05) and any value greater than 0.05 shows the normal distribution of data. Thus, it is confirmed that data belongs to a normal distribution.

Table 3-4 Summary of descriptive statistics of annual rainfall of Bahawalnagar

Parameter	**Sample Size**	**Mean ± SE_M**	**Mean ± SD**	**Skewness**	**$SE_{Skewness}$**	**Kurtosis**	**$SE_{kurtosis}$**
Annual Rainfall	40	281.89±22.70	281.89±143.59	0.488	.374	-0.258	.733

Table 3-4 is showing the normality analysis of annual rainfall data using SPSS in terms of skewness and kurtosis. These are the measures of non-symmetry and probability of outliers in data respectively.

Closer the values of Kurtosis and Skewness to zero, lower will be the deviation from the normal distribution. Skewness statistics of data came out as 0.488 from Table 3-8. As a rule of thumb, any skewness value lesser than 0.5 is considered to form a fairly symmetrical shape. While the kurtosis measure is -0.258, that is less but closer to zero so it tells that data is lightly tailed therefore data can be considered to follow the normal distribution.

Table 3-5 Descriptive statistics of monthly rainfall for Bahawalnagar station

Month	N	Minimum	Maximum	Mean		Std.	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Std.	Statistic	Statistic	Std.	Statistic	Std.
Oct	40	0.00	96.00	7.52	3.38	21.12	3.69	0.38	13.46	0.74
Nov	40	0.00	20.00	3.91	0.94	5.84	1.40	0.38	0.73	0.74
Dec	40	0.00	30.80	3.37	1.07	6.68	2.94	0.38	8.98	0.74
Jan	40	0.00	53.50	12.27	2.46	15.37	1.52	0.38	1.53	0.74
Feb	40	0.00	143.00	20.89	4.55	28.40	2.62	0.38	8.46	0.74
Mar	40	0.00	62.00	19.21	2.82	17.62	0.80	0.38	-0.37	0.74
Apr	40	0.00	73.50	13.23	2.52	15.75	2.05	0.38	4.95	0.74
May	40	0.00	113.30	15.86	4.15	25.94	2.71	0.38	7.63	0.74
Jun	40	0.00	197.50	38.13	7.50	46.81	2.03	0.38	4.42	0.74
Jul	40	0.00	263.10	69.72	9.63	60.16	1.28	0.38	1.61	0.74
Aug	40	0.00	216.00	44.13	7.56	47.20	1.63	0.38	3.27	0.74
Sep	40	0.00	242.00	33.65	9.05	56.50	2.18	0.38	4.63	0.74

Results for the monthly analysis of rainfall data for normality shown in Table 3-5 shows that the month of October has shown the maximum value of skewness that is the possible reason of slight unsymmetrical behaviour of data. Moreover, the higher value of kurtosis depicts the presence of outliers in the respective month.

Normal Q-Q plot for precipitation using SPSS is also analysed as shown in Figure 3-7.

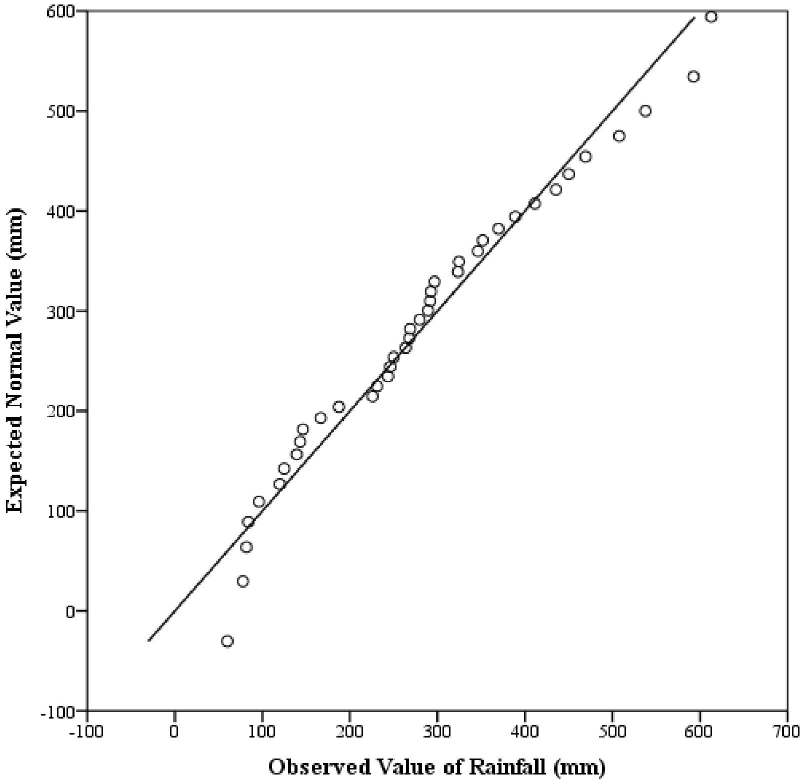


Figure 3-7 Normality Q-Q plot of annual rainfall of Bahawalnagar station

The Q-Q plot gives a graphical method to decide either the data is normal or not normal. The dark straight line in Figure 3-7 demonstrates the qualities our data must exhibit if it is believed to belong to a normal class of data. The unfilled circular marks are the points of actually acquired dataset. In the event that where the marks fall precisely on the dark line, at that point our data is following normality. If they deviate from the dark line, dataset deviates from normality. As most of the points are almost falling very close to the expected line thus data is normal. After the confirmation of normality, data is evaluated for consistency.

3.5.4 Analysis of consistency of data

Single mass curves were plotted for all the precipitation stations in a single chart to check the consistency of precipitation data and to analyse the relative variations as appeared in Figure 3-8. This is because that the connection between precipitation stations is typically communicated as a proportion, for example, it is said that one station normally has a specific portion of the precipitation at another station, the average value of the nearby stations, of a gathering of stations, or an averaged value of the area.

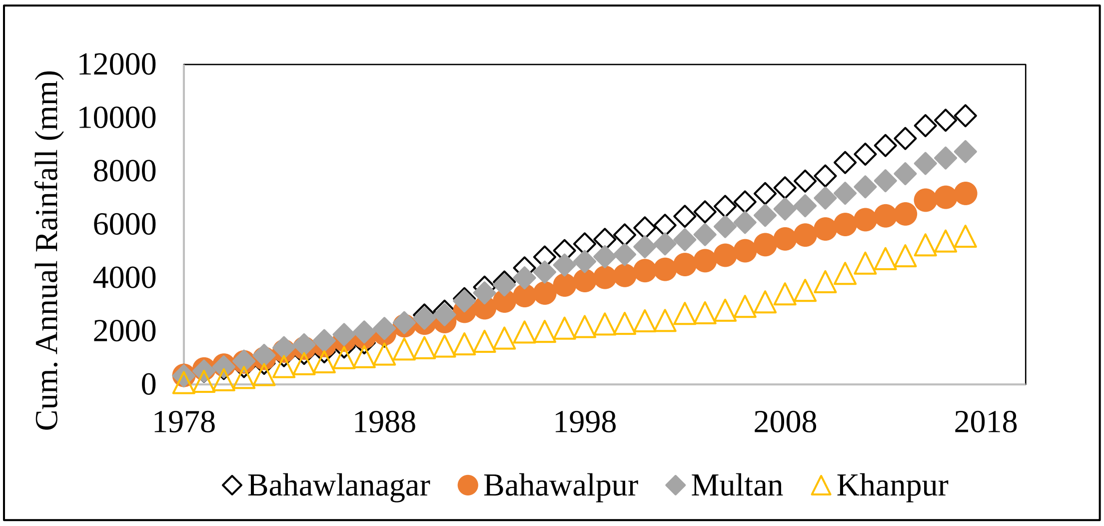


Figure 3-8 Single mass curves for rain gauging stations- Hakra canal study area

The consistency of the data is checked by the gradient of the respective curve. i.e. for the study area, Bahawalnagar station is the station of concern. The change in gradient of the curve after the year 1983 has shown that data is deviating from the straight line and there exist inconsistencies that need to be evaluated and corrected. Moreover, the correlation of Bahawalnagar station is calculated with the nearby stations as apparent from the single mass curve of Bahawalpur and Multan that came out as 0.650, and 0.630, respectively, while for the Khanpur station, the correlation coefficient came out to be 0.45 and therefore it is dropped for further calculations.

Double mass curve can be the best suited to analyse inconsistency in data (Chow, 1959; WMO, 1988, 2008). The consistency of a completed precipitation record is tested using double mass curve analysis. This strategy involved the analyses of accumulated yearly rainfall of suspected station with an accumulated average rainfall of neighbouring reference station. The reference station is normally the mean of a few neighbouring stations. The suspected station is the station of concern here in the study area; i.e. Bahawalnagar Station. Both the accumulated rainfall values for suspected and index stations are plotted on y and x- axis, respectively. Plot is analysed for pattern changes. With a steady record, the plot should follow a straight line and any breaks or variations from linearity depicts the inconsistencies in the dataset as we get in the undertaken dataset (Figure 3-9).

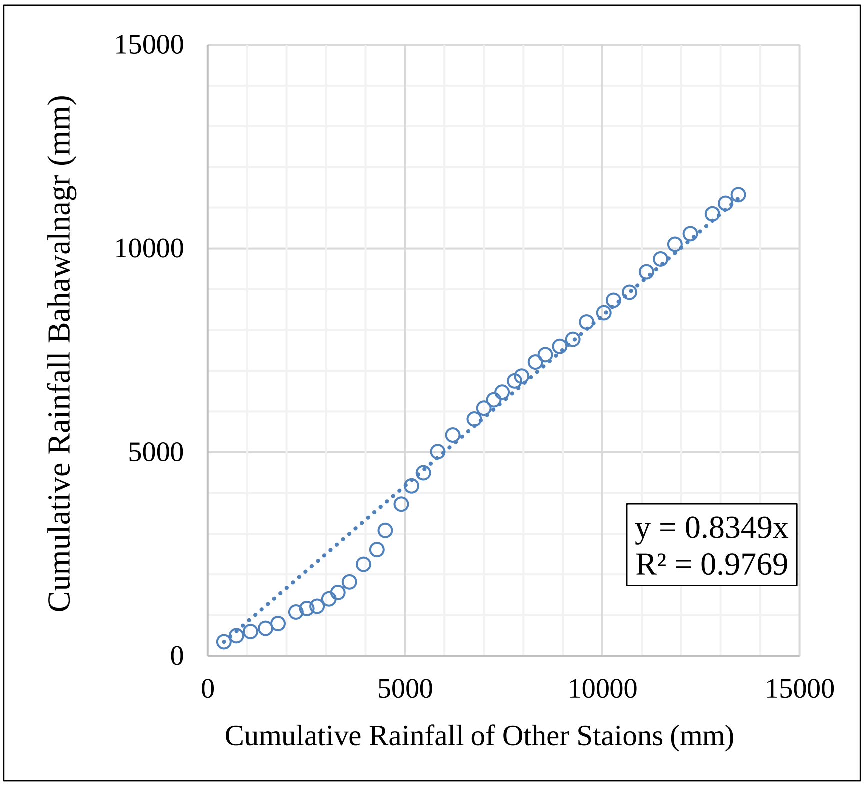


Figure 3-9 Consistency analysis of Bahawalnagar meteorological station data

Double Mass plot (Figure 3-9) demonstrated a break in slope, that showed that record at Bahawalnagar station is conflicting with the linearity and ought to be improved. The adjustment is performed by changing the records preceding the break to mirror the new state (after the break). To achieve this, the yearly precipitation information preceding the break are duplicated by the proportion of slope after and before the break; i.e. Slope correction factor adjusted precipitation. Figure 3-10 is showing the double mass curve of the slope factor corrected rainfall data.

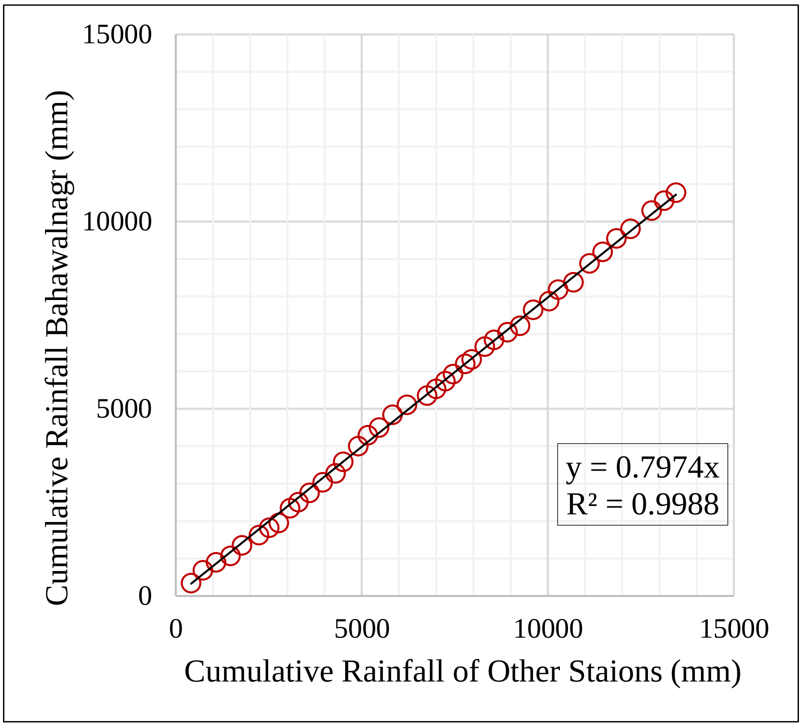


Figure 3-10 Double mass curve of adjusted rainfall data

The data adjusted to achieve sufficient consistency using the gradient factor is further utilized for the calculation of crop water requirement and climate variability.

3.6 Crop Water Requirement and Modelling With CROPWAT

Long-term average climatic data along with soil moisture holding capacity of the soil of study area is used to estimate the crop water requirement using CROPWAT 8.0 (FAO, 1992). The estimation of water requirement for crop growth would support the cautious application of accessible water and may diminish the overuse water from groundwater storage.

Crop water requirement is estimated in terms of evapotranspiration less effective rainfall. Initially, the reference evapotranspiration (Et_o) from meteorological data based on widely accepted Penman-Monteith equation is estimated as given in Equation 6 and 7. It gives the long-term average reference evapotranspiration (ET_o) for the study area. Shakir and Qureshi (2007) say that this method has more likelihood of predicting relatively better values of reference evapo-transpiration (ET_o) thus provides reliable results, as defined by;

$$\mathrm{ET_o} = \frac{0.408\,\Delta\,(\mathrm{R_n} - \mathrm{G}) + \gamma\,\dfrac{900}{T + 273}\,u_2\,(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{Eq.6}$$

$$ET = \mathrm{K_c}\ \times \mathrm{ET_o} \tag{Eq.7}$$

where,

$\mathrm{ET_o}$ = Reference Evapotranspiration [mm day^{-1}],
Δ = Slope vapour pressure curve [kPa °C^{-1}],
$\mathrm{R_n}$ = Net irradiance [MJ m^{-2} day^{-1}],
G = Soil heat flux density [MJ m^{-2} day^{-1}],
Γ = Psychrometric constant [kPa °C^{-1}],
u_2 = Wind speed at 2 m height [m s^{-1}],
T = Air temperature at 2 m height [°C],
e_s = Saturation vapour pressure [kPa],
e_a = Actual vapour pressure [kPa],
ET = Actual Evapotranspiration [mm day^{-1}], and
$\mathrm{K_c}$ = Crop Coefficient.

The effective monthly rainfall (Pe) for the area was derived from the total monthly rainfall (P) using equations of USDA soil conservation services as given in equation 8a and 8b;

$$Peff = \frac{P * (125 - 0.2 * 3 * P)}{125} \qquad for\ p \le \frac{250}{3} mm \tag{Eq.8a}$$

$$Peff = \frac{125}{3} + 0.1 * P \qquad for\ p > \frac{250}{3} mm \tag{Eq.8b}$$

where,

$\mathrm{P_{eff}}$ = Effective rainfall in mm, and

P = Observed rainfall in mm.

Evaporation and transpiration happen at the same time and there is no simple method for recognizing the two processes separately. Aside from the water accessibility in the topsoil, the dissipation from a cultivated soil is for the most part controlled by the sun powered radiation arriving at the cultivated soil surface. This part diminishes over the developing time frame of the crop as the harvesting time approaches and the crop cover increasingly shield more of the ground territory. At the point when the growth is little, water is predominately lost by soil evaporation, however, once the crop grows and totally covers the soil, transpiration turns into the primary procedure.

At the point when adequate dampness is uninhibitedly accessible to totally address the vegetation fully grown and not short of water, the subsequent evapotranspiration is called Potential evapotranspiration (PET), while in the field, the evapotranspiration happening is known as the actuals evapotranspiration (AET). It has been additionally settled that PET relies on the climatologically factors, while the AET to a great extent influenced by the qualities of soil and vegetation. Thus, another important aspect of the crop water requirement is the soil type. The characteristics of soil types present in the area are tabulated in the Table 3-6.

Table 3-6 Characteristics of the soils in the study area

Soil Type	Parameter	Value	Unit
Loam	Soil moisture at field capacity (SMF)	96.52	mm/m
Loam	Soil moisture at wilting point (SMW)	29.9	mm/m
Loam	Depletion	69	%
Loam	Infiltration rate	360	mm/d
Sandy Loam	Soil moisture at field capacity (SMF)	60.96	mm/m
Sandy Loam	Soil moisture at wilting point (SMW)	21.9	mm/m
Sandy Loam	Depletion	63.5	%
Sandy Loam	Infiltration rate	600	mm/d

Soil type determines the infiltration rate, rooting depth, soil moisture at field capacity and soil moisture at wilting point. After georeferencing the soil map of the zone, major soil types in the study area are identified. The soil of the area is mainly sandy loam ~ loam. By looking into literature and FAO guidelines, the prepared soil attribute table is verified with the experienced personnel. Seepage and percolation losses from loam are taken as 6 mm/day as per Brouwer et al. (1986).

The staple crops grown on study area are wheat and cotton while other crops include rice, sugarcane, and seasonal fodder. The pre-processed data of the land cover is obtained from the Irrigation Department, Pakistan and the land area covered by each crop in an annual cycle is extracted from the obtained file. Land cover of the study area is given in the Table 3-7.

Table 3-7 Land cover details of the area

OID	Land cover type	Area Covered (Ha)
0	Urban/bare land	53525.07
1	Multiple rice	1379.43
2	Natural vegetation	17135.37
3	Orchards	20723.67
4	Perm. or seasonal water	753.30
5	Sugarcane	528.03
6	Wheat	12500.01
7	Wheat and Cotton	146200.86
8	Wheat and Maize	3592.53

Major crops of the area are wheat and cotton. Wheat is grown in Rabi season (Oct~ March), while Cotton is the Kharif crop grown in the months of April to October. October is the overlapping period for the cultivation of wheat and harvesting of cotton. Other crops include rice, sugarcane and fodders for the seasons; i.e. Barseem and sorghum. Figure 3-11 is showing the landcover map of the area.

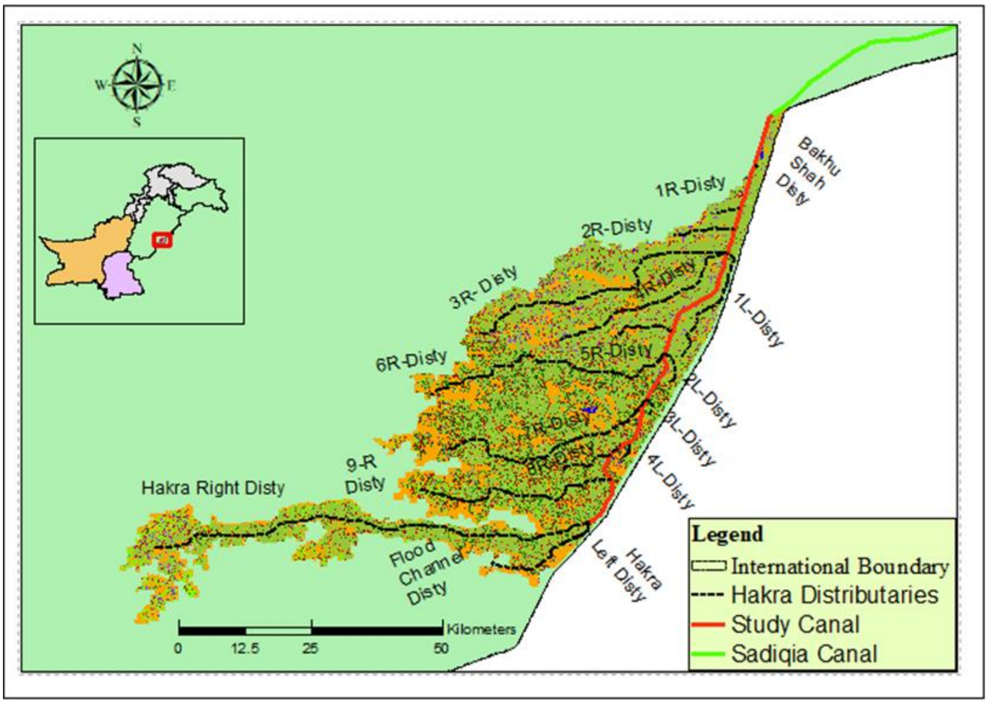


Figure 3-11 Landcover map of the study area

Table 3-8 is showing the crop coefficient used for the specific study area depending on the crop growth stages. For realistic values of crop coefficient, Punjab Agricultural Department's annual reports and FAO guidelines are consulted.

Table 3-8 Monthly crop coefficients for consumptive use of crops

Crop Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sugarcane	0.68	0.44	0.31	0.34	0.51	0.91	1.30	1.17	1.15	1.02	0.38	0.36
Cotton	0	0	0	0.35	1.2	1.15	1.20	1.2	0.70	0.5	0	0
Orchard	0	0	0	0.75	0.75	0.75	0.70	0.70	0.75	0.75	0.75	0
Sorghum	0	0	0	0	0	0.53	1.13	0.82	0	0	0	0
Rice	0	0	0	0	0	0	0.64	1.10	1.23	1.12	0	0
Maize	0	0	0	0	0	0	0.22	0.62	1.06	0.90	0	0
Wheat	0.53	0.78	0.97	0.56	0	0	0	0	0	0	0.14	0.40
Barseem	0.94	0.98	1.01	1.01	0	0	0	0	0	0	0.43	0.52

Crop water requirements for the Hakra canal system required to fed by irrigation system have been worked out using average cropping intensities for the past ten years and specific crop coefficients based on the crop cover of the study area. Literature has reported the value of irrigation efficiency in Pakistan varying from 35 % to 55 % (Hussain, Hussain, Sial, Akram, & Farhan, 2011). For the undertaken study, the average efficiency of 42.5 % is considered for the irrigation system. Figure 3-12 is showing the cultivation plan opted for study based on previous practices.

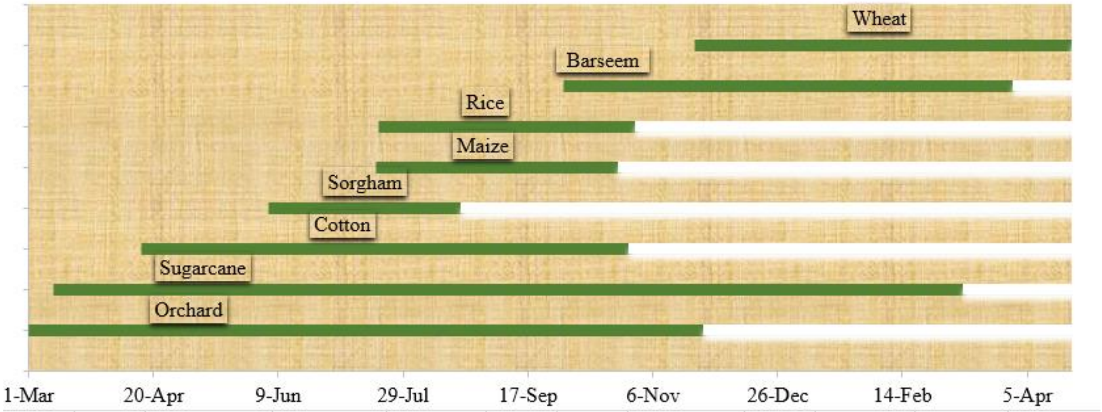


Figure 3-12 Typical cropping pattern prepared for the area

Rooting depth shown in Table 3-9 is important to analyse as it shows the ability of a plant to grow deep in the soil and can uptake water through capillary action.

Table 3-9 Specific rooting depth of the land cover of the study area

Crop type	Rooting depth (m)
Citrus	1.1
Fodder	0.8
Maize	0.9
Rice	0.5
Cotton	1.0
Sugarcane	1.2
Wheat	1.0
Sorghum	1.0

All the data collected and prepared is collectively used to work out the crop consumptive use and actual irrigation requirements. Actual irrigation requirements are the gross irrigation requirements less effective rainfall.

3.7 Evaluation of Canal Water Sufficiency and Groundwater Contribution

After the Indus basin treaty in 1960, based on the historic water use of provinces, an accord is agreed upon by the representatives of the four provinces of Pakistan in 1991. That “Water Apportionment Accord” describes distribution of waters of Indus river among provinces (Nadeem, 2010).

3.7.1 Canal entitlements and deliveries

A systemwide seasonal entitlement or the share is further suggested to be worked out by the provincial governments as a follow-up of the agreement. For that, “Indus River System Authority (IRSA)” is formulated that is responsible for seasonal allocations and distributing and communicating shortages as per provincial share.

The IRSA operates by collecting the observed data from respective irrigation departments. After consultation with Water and Power Development Authority (WAPDA), and provincial irrigation department, the ISRA formulates a seasonal allocation plan prior to the start of cropping seasons; i.e. Kharif and Rabi. Due consideration is given to the available storage of water in the water reservoirs. Therefore, the right gauge recording and releases of the supplies accessible in rivers and those pulled back by the different canal is critical, as this information shapes the reason for the allotment of water to provinces, head controller at canals and for the constant upgrade of agrarian efficiency of irrigation network. An adjusted seasonal share of Hakra canal in million-acre feet prepared by the provincial government of Punjab is given in Figure 3-13 and Figure 3-14.

Hakra canal is a branch or secondary canal originating from Eastern Sadiqia canal. Eastern Sadiqia canal gets its supply from link canal since partition as Indus water treaty has given rights of Sutlej river to India.

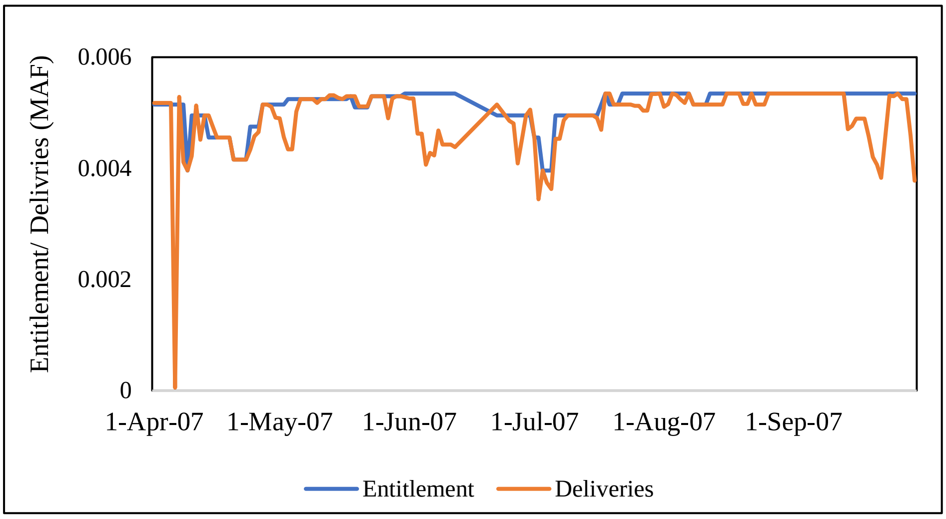


Figure 3-13 Actual and tentative distribution programme of water for Kharif season

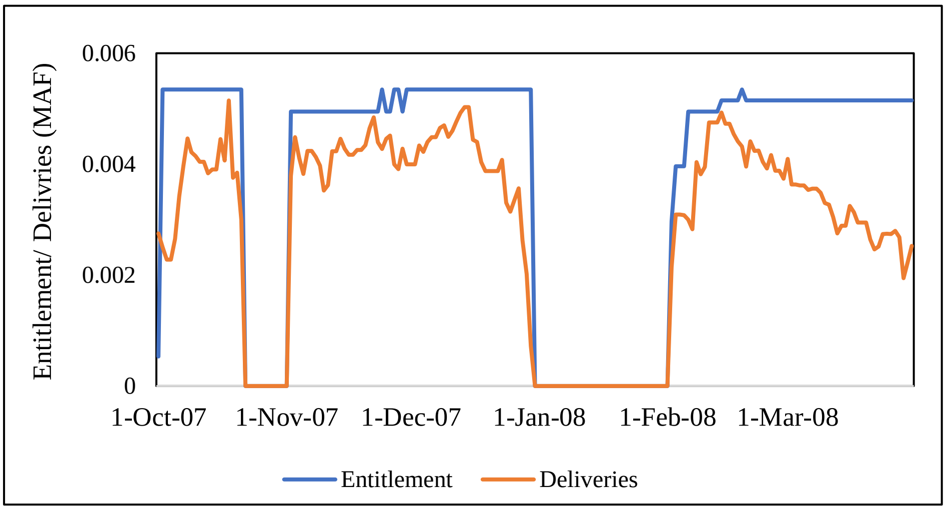


Figure 3-14 Actual and tentative distribution programme of water for Rabi season

In Kharif, the shortfall is provided by redirection water from the river Chenab and passed on through Link channels to the Sutlej River. In Rabi, the water originates from the Mangla Dam,because supply is very limited in the winter season.

3.7.2 Groundwater requirement and estimation

Hakra canal allocated historic discharge values and actual deliveries to canal are collected from the Punjab Irrigation Department. Discharge data is manipulated on the monthly time scale and a comparison is made with the actual estimated irrigation requirements in appropriate units; i.e. BCM for the period of past 10 recent years 2008~ 2017.

The deficit to the total irrigation requirements is estimated in terms of groundwater contribution on monthly basis for the same data period (2009~ 2017). To verify the estimated contribution from groundwater, the comparison is made with the monitored groundwater depth for the individual year.

3.8 Evaluation of Climate Variability

The atmosphere of Pakistan has turned out to be progressively harsh in ongoing decades. The extent and constancy of the progressions need to be analysed to infer that there exists a nonstationarity in climate. Homogeneity test tells us about any trend followed by the dataset or sudden changes if present in the data. Statistical test can be used to access such points of variability or change along with historical or physical support from meteorological data (Wijesekera & Perera, 2012). These procedures help in accessing the future scenario for the sampled system by establishing a quantitative relationship between the measurements and characteristic of the system.

Statistical tests for non-homogeneity assessment may be of parametric or non-parametric in nature and the preference to use a particular class depends on the normality of data involved (Wijesekera & Perera, 2012).

A set of data following normal distribution can be assessed for identifying any available trend by parametric tests; e.g. Student's t-test, One-way ANOVA, etc. If the data is not following the normal distribution, then nonparametric methods can be better representative of the trend; e.g. Mann-Kendall, Mann-Whitney and Sen's slope, etc. (Robert, Alexander, & Smith, 1991). For hydrologic set of data disobeying normality more often, a choice of distribution free methods is preferred (Wijesekera & Perera, 2012). In this regard, Mann-Kendall Test is widely accepted and applied to analyse the significance of the statistical trend.

Mann-Kendall, a non-parametric test devised by Mann (1945), is usually employed to assess the presence of monotonic trend in the series of given data. The application of this test has widely been accepted in the field of water resources and hydrology (Robert et al., 1991). This test is carried out based on null hypotheses that data is not following a monotonic trend. Hypothesis is rejected or accepted based on level of significance.

Theil-Sen slope estimator or slope selection method is used to fit a line to the sample points (Gul et al., 2018; Hasan, 2013; Hirsch et al., 2002). The method of fitting the line considered the median slope of all the data points. Mann-Kendall and Sen’s Slope tests are simple, vigorous and can cope with missing data to some extent. The output of these tests is not affected by the presence of extreme values (Machiwal & K.JHA, 2009). Chow (1964) asserted the moving averages method to be widely used to assess the presence of a trend.

The observed climate data especially rainfall and temperature over the study period (1978-2017) from the Bahawalnagar station need to be preliminarily inspected for normality and consistency before analysing the ongoing trends and expected sudden changes in the consumptive use of crops and insecure irrigation supply.

In order to analyse and study any existing trend, data is assessed for normality. Thus, to evaluate the trend and its magnitude in the data after filling Mann-Kendall and Sen’s Slope methods with 95% confidence level need to be utilized respectively. Mann-Kendall and Sen’s slope estimates are utilized to display the presence of monotonic increasing or decreasing trends in climate data and their significance and severity level.

3.9 Results Verification using Hydrological Modelling

Lower portion of this widespread IBIS is currently one of the most water-focused regions on the planet and probably going to turn into a water scarce zone (Briscoe et al., 2006). Previous anomalous episodes have given rise to the risks of dry spells, flooding or both in the region. Recently a flood is experienced in 2010. High populace development in Pakistan especially in the downstream areas and developing effects of climatic fluctuation upstream have created expanding weight on the water supply from the Indus River Basin framework.

3.9.1 Selection of catchment

Pakistan is most reliant on water originating in high mountain catchments and in this manner, most vulnerable against climatic and other worldwide changes upsetting the supply and demand cycle. For instance, the flow in Sutlej is constrained by Himalayan snowmelt in spring and summer and south-Asian monsoon. The lower contribution from snowmelt and precipitation in winter significantly reduce the overall flow. Bhakra Dam built on Sutlej in Indian territory receives around 59% of the flow from the melting of icy masses. The flow in Sutlej is highly conditional to both temperature and precipitation changes as well.

Flow is majorly produced in Indus basin to a huge degree by snow melting while the contribution because of precipitation fluctuates relying upon the season. Moreover, environmental change effects are probably going to be serious in the cryosphere and on the water supplies dependent on these snow masses (Immerzeel, Van Beek, & Bierkens, 2010; Rees & Collins, 2006). Therefore, a well-defined snow dominant catchment in the upstream of the canal command area is selected (Figure 3-15).

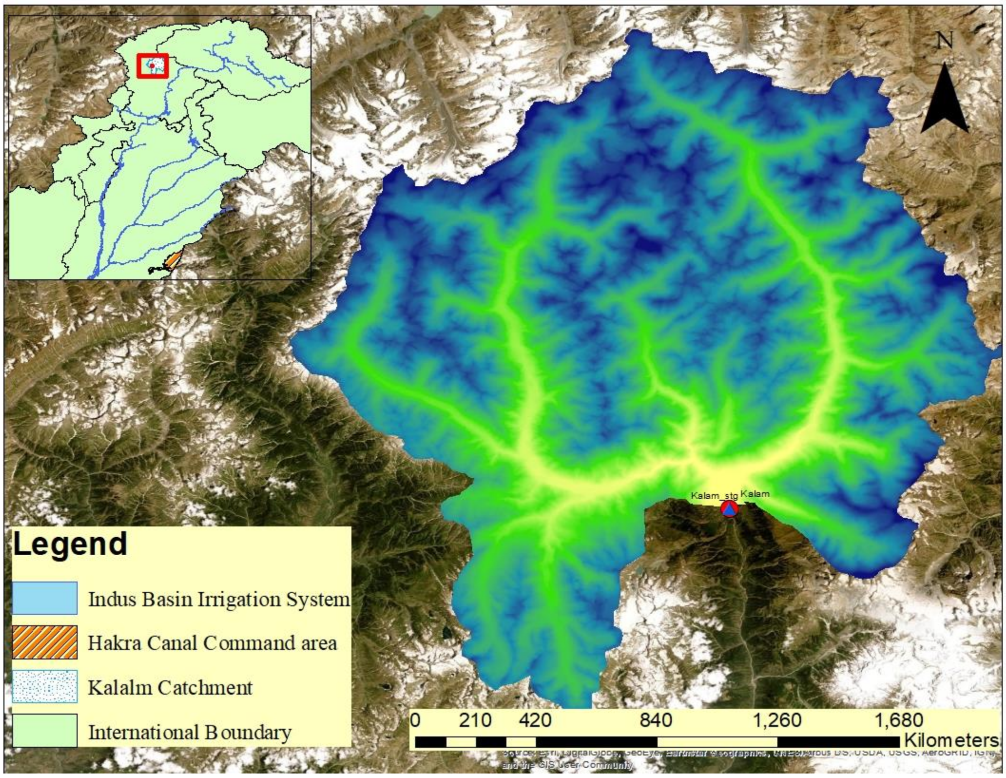


Figure 3-15 Kalam catchment in the upstream of IBIS

Icy mass melts vigorously affect the runoff of the downstream river as well as the discharge from the reservoir.

Selection from an upstream basin in Terbala catchment is carried out as these catchments of Mangla and Tarbela dams have genuinely well-created catchments. Management practices and their developments require improved comprehension of the hydrological cycles to keep up the harmony between supply framework in upper catchments and demand system in the downstream. A detailed map of the selected study area and catchment basin for the verification of climatic variability is shown in Figure 3-16.

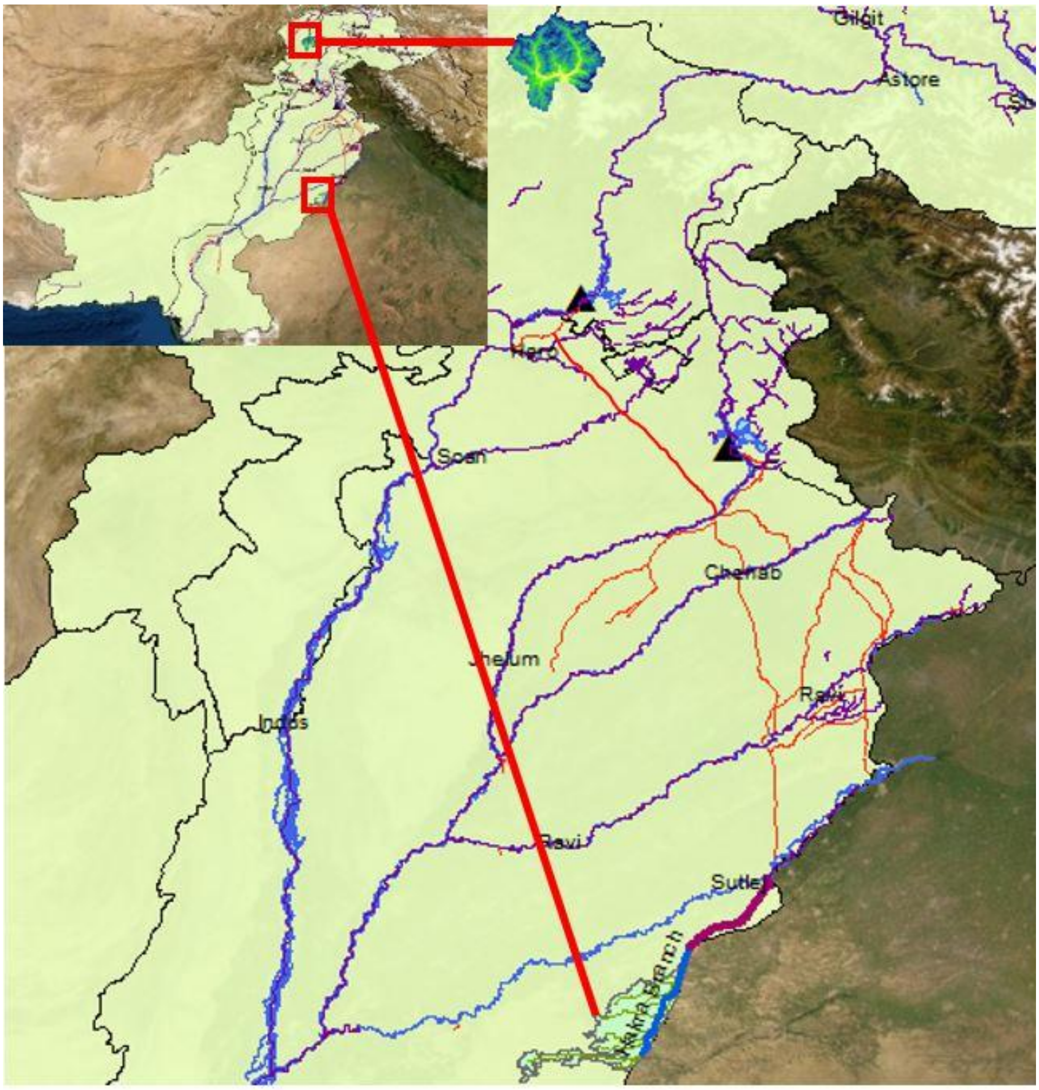


Figure 3-16 Upstream Kalam catchment and downstream Hakra canal command area in IBIS

Due to unreliable supply from the Sutlej and Ravi transboundary rivers after Indus water treaty, the link canals shown in red colour in Figure 3-16 are constructed to deliver the water from western rivers, i.e. Chenab, Jhelum and Indus river, to the irrigated area of eastern rivers in Pakistan. The water reservoirs in the basin are shown by the black triangular symbols. The water release to these canals from the upstream water reservoirs is highly dependent on the input to those reservoirs from snowmelt in the upstream basin, i.e. Kalam. The schematic diagram of the system is shown in Figure 3-17.

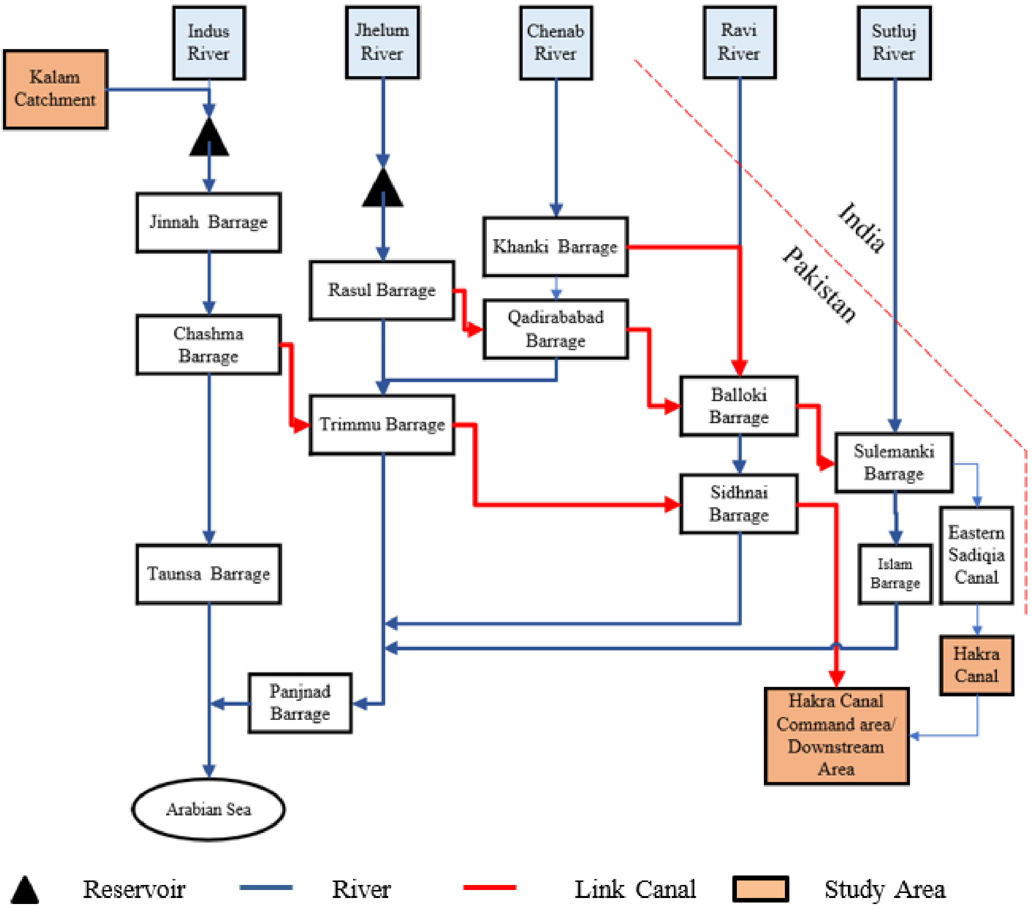


Figure 3-17 Schematic diagram of the selected basin

Kalam is an absolutely snow fed catchment so it is imperative to screen or compute snow release that can give supportable supply to stream release and downstream irrigation water system. Moreover, the consideration to build the storage reservoirs in the upstream to store snowmelt to provide additional water to the downstream irrigated area can only be implemented after a thorough investigative study of climate variability in the upstream catchment. Therefore, selected upstream catchment is suited best to the undertaken study.

3.9.2 Hydrological modelling

Hydrological analysis is carried out in order to verify the predicted climate variability within the Hakra canal command area. The process follows the development of a hydrologic model for the upstream catchment and model optimization. Later, the well optimized model is used to analyse the variations in the hydrological process within the catchment. Hydrological analysis will predict and anticipate the changes in hydrological processes caused due to climate change. Conclusions drawn based on hydrological analysis is helpful to verify the predicted changes in the downstream in Hakra canal command area.

The selected catchment is snow dominant with prevailing data scarce conditions. Out of numerous rainfall-runoff models, the four parameter model (modified with snow model component) (‘*abcdm*’) which is a physics based lumped model is used for hydrological analysis for the present study since it can sensibly screen the reaction of a catchment under the climate change scenario and also has the ability to incorporate the snow with a little modification.

To date, in more than 500 catchments situated in various counties and regions, the model has been applied by different organizations and colleges. Practically, half of these investigations have been carried out in the USA, Spain and Switzerland

The governing equations of the four parameter model are given in Equation 9,10 and 11.1,11.2, and 11.3 and 12.1. 12.2 and 12.3. The model governing equations are;

$$P_t - E_t - R_t - QU_t = XU = XU_t - XU_{t_{-1}} \qquad \text{(Eq.9)}$$

$$EO_t(WA_t) = \frac{WA_t + b}{2a} - \sqrt{(\frac{WA_t + b}{2a})^\wedge 2} - \frac{WA_t - b}{a} \qquad \text{(Eq.10)}$$

$$(PS_t) = 0 \text{ if } T_{rain} < T_{min} \qquad \text{(Eq.11.1)}$$

$$(PS_t) = \mathrm{PT_t}\,.\frac{T_{rain} - T_{min}}{T_{rain} - T_{snow}} \quad \text{if } T_{snow} \leq T_{min} \leq T_{rain} \tag{Eq.11.2}$$

$$(PS_t) = \mathrm{PT_t} \ \text{ if} \, T_{min} < T_{snow} \tag{Eq.11.3}$$

$$SM_t = 0 \; if \; T_{min} < T_{snow} \tag{Eq.12.1}$$

$$SM_t = (XS_t - 1 + PS_t).m.\frac{T_{rain} - \ T_{min}}{T_{rain} - T_{snow}} \; if \; T_{snow} \leq T_{min} \leq T_{rain} \tag{Eq.12.2}$$

$$SM_t = (XS_t - 1 + PS_t).m \;\; if \; T_{rain} \leq \ T_{min} \tag{Eq.12.3}$$

where,

P_T = Monthly precipitation,

E_t = Actual evapotranspiration,

R_t = Recharge to groundwater storage,

QU_t = Upper zone contribution to runoff,

XU_t = Upper soil zone soil moisture storage at the current time steps,

XU_{t-1} = Upper soil zone soil moisture storage at the previous time steps,

T_{rain} = Temperature at which precipitation falls as liquid water,

T_{snow} = Temperature at which precipitation falls as snow, and

T_{min} = Minimum average temperature of the month.

4 RESULTS AND ANALYSIS

4.1 Reference Evapotranspiration and Rainfall Contribution

Evapotranspiration and precipitation are essential elements of the water cycle. Reference evapotranspiration is estimated from the metrological data and it is the representative of the evapotranspiration from a reference crop such as green grass at its optimum growing conditions; i.e. fixed surface resistance with no shortage of water and active growth, etc. Effective rainfall is the quantity of rainfall that an area can expect to be actually contributing to its overall water requirement for crop production. The estimated values of reference evapotranspiration represented as ET_o and effective rainfall during a water year (Apr ~ Mar) for the Hakra canal system using CROPWAT 8.0 are shown in Figure 4-1. The effective rainfall of the study area is 296 mm comparative to the reference evapotranspiration value of 1,564 mm annually.

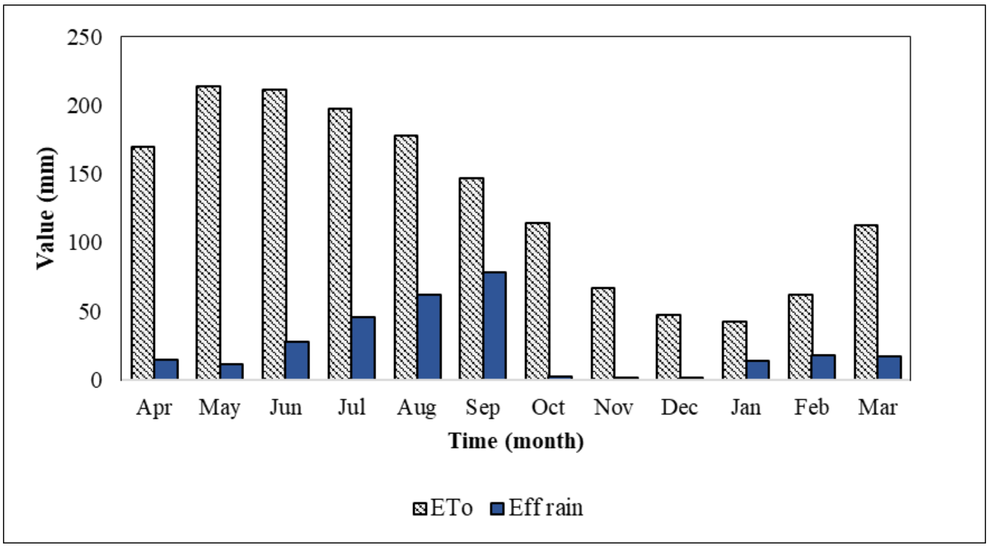


Figure 4-1 Reference evapo-transpiration (Et_o) and effective rainfall (P_e) for Hakra canal system

From the figure, it is apparent that the highest amount of effective rainfall received during monsoon is around 70 mm in the considered study area of Hakra canal that is predominantly an agricultural area. Further, the reference evapotranspiration, a factor of climatic conditions of the area, is very high comparative to the rainfall received by the area. Therefore, it is conclusive to say that area is predominantly dependant on irrigation water for the agricultural activity in both cropping seasons, whereas negligible amounts of irrigation requirements can be fulfilled by the precipitation.

4.2 Estimation of Actual Crop Evapotranspiration

Using a specific crop, its crop coefficient and the moisture conditions based on the soil type of the area the actual evapotranspiration values for each crop are worked out. An accurate and realistic estimation is a basic requirement to upgrade the historic supply-based system of water distribution with a demand-oriented system. Estimated crop evapotranspiration values are tabulated in Table 4-1 along with literature based average values from different regions.

Table 4-1 Estimated crop evapotranspiration

Crop	Estimated ET (mm/year)	Value from literature (mm/year)
Sugarcane	1245	1202
Cotton	1016	1160
Orchard	---	906
Sorghum	482	482
Rice	632	632
Maize	413	413
Wheat	304	276
Barseem	525	387

The Rabi or winter crops, i.e. Wheat, Barseem, have higher values of evapotranspiration for the study area comparative to the average values of the other regions. The reason is apparently the harsh climatic condition where the average temperature of the cold months (Dec-Feb) usually remains over 15^{o} C, while the maximum day temperature remains above 20^{o} C. A comparison is made between the reference and actual crop evapotranspiration. The estimated values of ET_{o} and crop evapotranspiration for the Hakra canal system are shown in Figure 4-2.

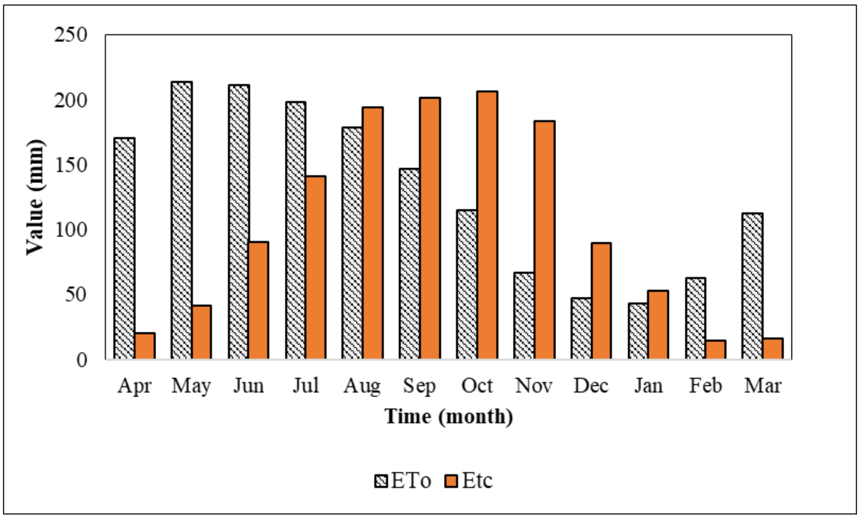


Figure 4-2 Reference and crop specific evapotranspiration

4.3 Consumptive Use of Crops and Actual Irrigation Requirements

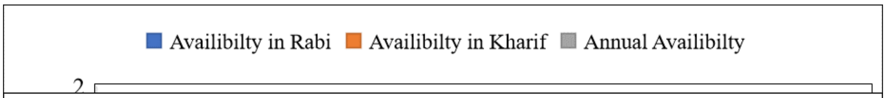
Gross irrigation requirements are worked out for the Hakra canal system and tabulated as given in Table 4-2. Currently, precipitation is only sufficient to account for 20 % of the total actual irrigation requirements, while the rest of the irrigation requirements are dependent on the irrigation of fallow land.

Table 4-2 Actual monthly irrigation requirements and effective rainfall of area

Month	**Crop Evapotranspiration (mm/month)**	**Effective Rainfall (mm/month)**	**Net Irrigation requirements (mm/month)**
Jan	20	11	9
Feb	41	14	26
Mar	90	14	76
Apr	141	12	113
May	194	9	184
Jun	202	23	176
Jul	206	37	164
Aug	183	51	125
Sep	90	65	24
Aug	53	2	51
Oct	53	2	51
Nov	14	1	13
Dec	16	2	14
Annual	1251	241	976

4.4 Evaluation of Adequacy of Delivered and Allotted Canal Water

Daily canal water supplies are summed for the annual and seasonal basis and represented in terms of volume available to the irrigated land in billion cubic meters. The volumetric terms are easier to interpret and understand by the farmers. Figure 4-3 is showing the actual available water to the land. There are even discrepancies between allocated water and the water which is available at the canal. Mean annual canal allocation or allocated water is around 2 billion cubic meters as shown in Figure 4-3, while actual water reaching to canal head has a mean value of 1.6 billion cubic meters.



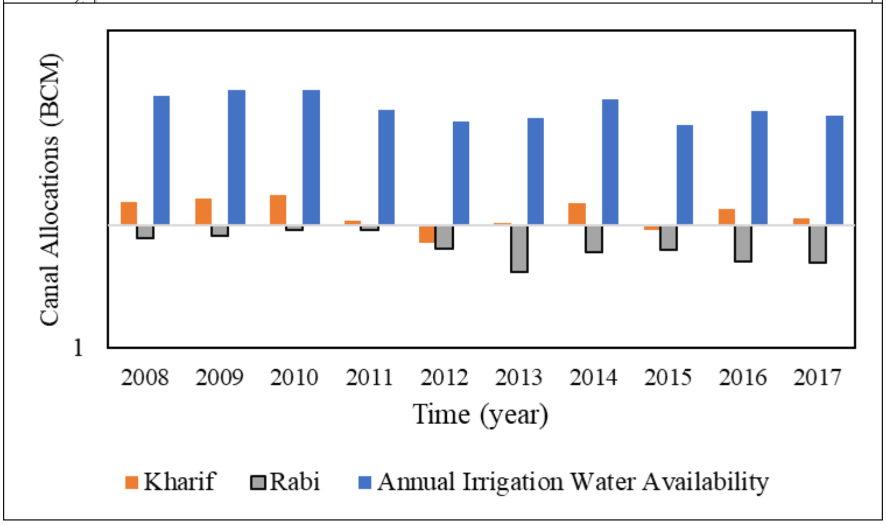


Figure 4-3 Annual and seasonally availability of water to irrigated land

Figure 4-4 Yearly water allocation for canal

The availability of the flow in Rabi season has shown a decreasing trend. In Rabi or winter season, the flow is predominantly produced due to the snowmelt from the glaciers and icecaps. The possible reason for lower flow in the Rabi season is due to low water release in the river due to limited or no amount of precipitation.

Comparison of canal water allocation, actual water availability and irrigation water requirements on a seasonal basis is carried out as shown in Figure 4-5 and Figure 4-6.

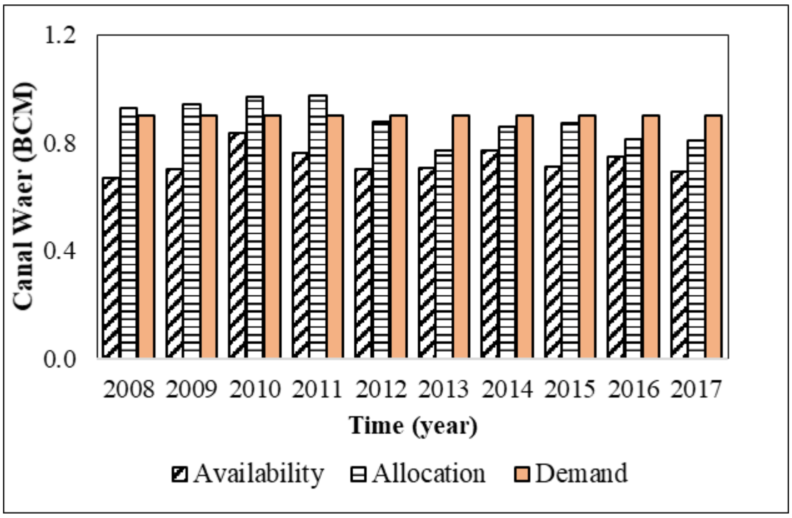


Figure 4-5 Comparison of canal water allocation, actual water availability and irrigation water requirements for Rabi Season

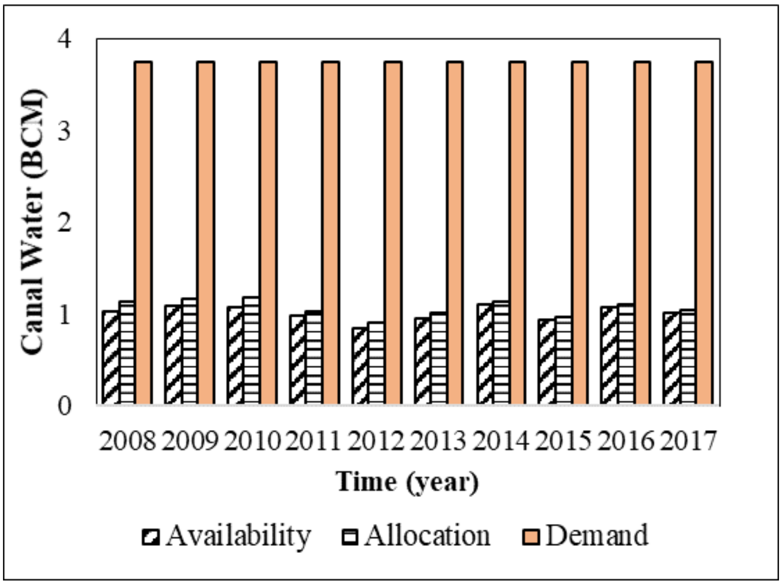


Figure 4-6 Comparison of canal water allocation, actual water availability and irrigation water requirements for Kharif Season

From the Figures, it is apparent that during Rabi season, the allocation or delivery is somehow comparable to the actual requirement. However, a significant reduction has been observed after 2011 in the supply as well as allocation. This reducing trend is due to the reduction of flow available at the source, i.e. Sutlej river. Fruther, during the Kharif season (Apr ~ Sep) that is a cultivation season of water intensive crops such as cotton and rice, there is a huge disparity between the supply and demand throughout the study period (2008~ 2017). In other words, the gap between the quantities needed and required need is to be filled by another source, i.e. groundwater.

4.5 Estimation of Groundwater Contribution & Verification

Groundwater contribution is estimated for the study duration of (2008~ 2017) using a simple water balance approach. The following Equation 13 has been used to quantify the rate of water contributed by the groundwater abstraction. Estimation of groundwater abstraction is carried out on monthly basis, using;

$$ET_c - ICW_{net} - P_{eff} = IGW_{net} \qquad \text{(Eq.13)}$$

where,

ET_c = Crop consumptive use (mm/d),
ICW_{net} = Net canal water irrigation (mm/d),
P_{eff} = Effective precipitation in (mm/d), and
IGW_{net} = net groundwater irrigation (mm/d).

Groundwater contribution for each year is estimated individually as the channel flow varies from year to year. On an annual basis, there are no huge variations, but the monthly contribution is highly variable from the minimum value of abstraction in February while highest abstraction took place in the month of May as per the estimations. Estimation in terms of the difference between abstraction and recharge are reported as positive and negative values. Positive values are showing the months where the groundwater is abstracted to compensate for the deficit while negative values are the recharge to the groundwater. On average, groundwater contribution is 35% for the study period (2009~2017).

The average amount of groundwater abstraction or recharge is given in Figure 4-7. Estimation revealed the months of September, November and December as the months of surplus flow from irrigation channel and that flow has contributed to groundwater recharge.

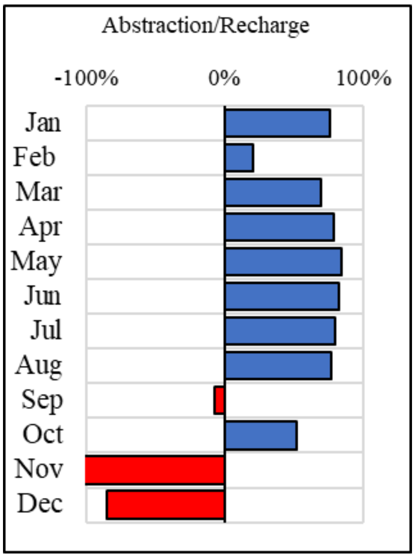


Figure 4-7 Estimated groundwater abstraction/ recharge based on root zone water balance

4.6 Climatic Analysis of Hakra Canal Area

The apparent high variability between the channel flows and subsequent groundwater extraction need to be evaluated. The purpose is to discover the underlying causes giving rise to this disparity in addition to inherent water shortage. The climate of the area has been reported vulnerable to climate change. To evaluate and confirm any kind of climate variability the precipitation, the maximum, minimum and average temperature are analysed.

4.6.1 Analysis of rainfall anomaly

Rainfall data is analysed for anomalies to observe any deviations from the historic mean values on seasonal and annual basis. Total average annual rainfall (1978～2017) over the area has shown an increasing trend as shown in Figure 4-8.

As the precipitation in Pakistan is highly variable, the seasonal analysis of data is carried out in two ways. The one class contains the seasonal analysis of the rainfall based on cultivation season namely Rabi and Kharif. The other seasonal classification is based on temperature-based climatically varying seasons throughout the year as described by Shamshad (1988) and Khan et al., (2010).

Temperature based varying seasonal classification taken into consideration is as follows

1. The winter season from December to February
2. The spring season from March to April
3. Dry summer from May to June
4. The rainy monsoon season, which lasts from July to September
5. The autumn season from October to November

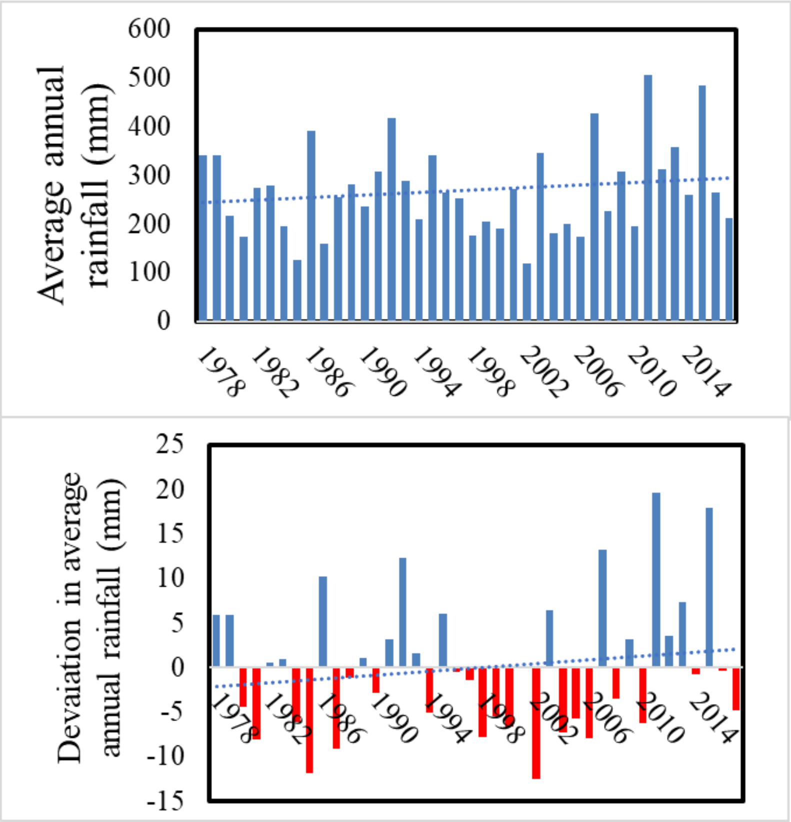


Figure 4-8 Deviation of average annual rainfall

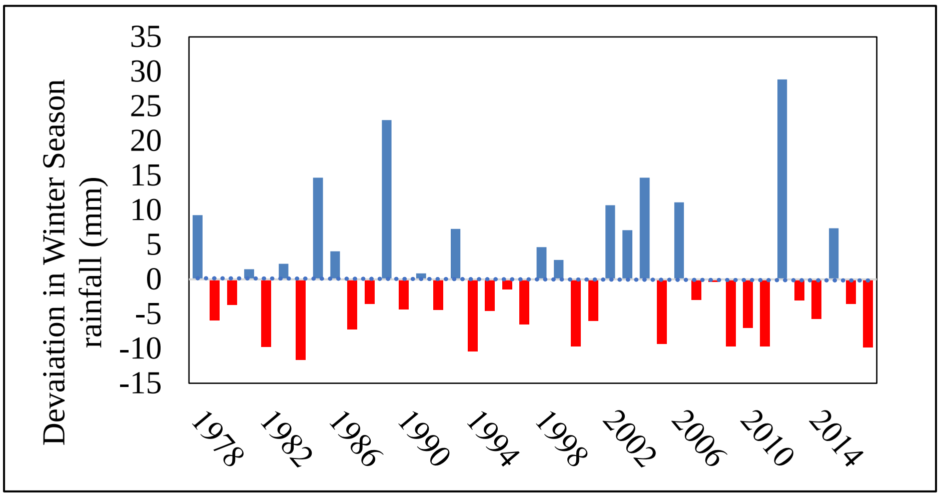


Figure 4-9 Precisely decreasing trend in winter rainfall (Dec-Feb)

Figure 4-9 is showing the hardly discernible decreasing trend of winter rainfall in Bahawalnagar region. Apparently, this trend grows significantly with the increase in temperature in the subsequent spring season (March-April) with the less contribution of rainfall (Figure 4-10).

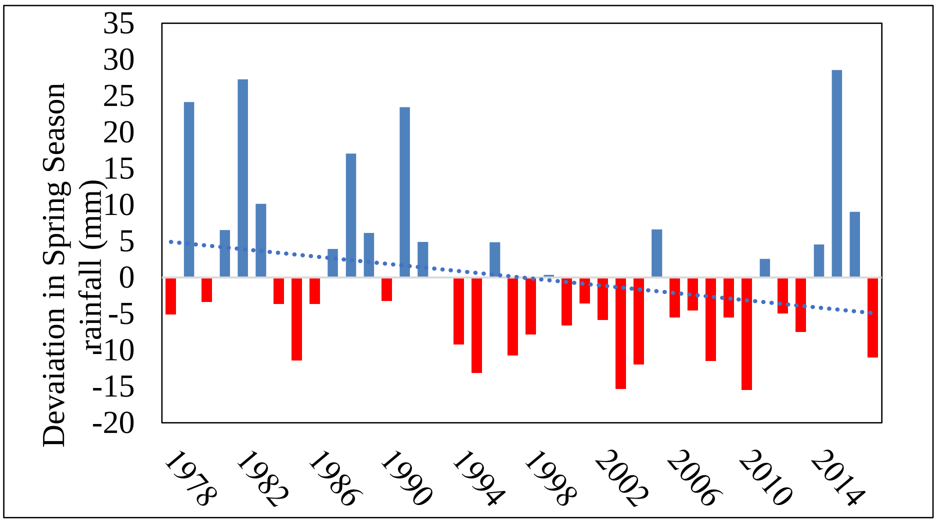


Figure 4-10 Visually trend in rainfall during the spring season

As, the temperature further gets higher and the monsoon season approaches, historic rainfall has shown an increasing trend as observed during the dry summer and monsoon period of rainfall Figure 4-11. Both the consecutive seasons has shown an increment in average rainfall over the study period.

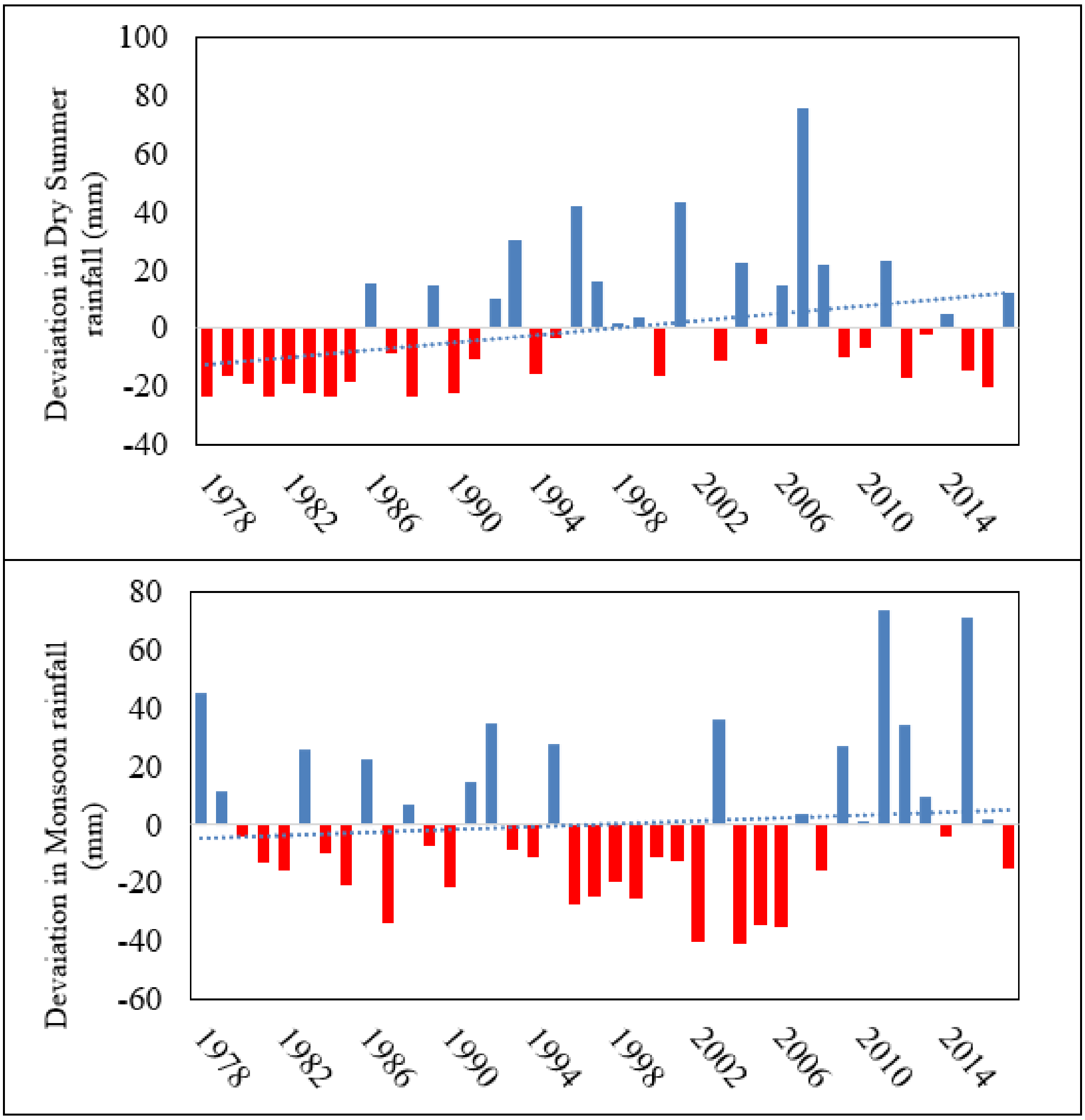


Figure 4-11 Seasonal rainfall trend in dry summer and monsoon

Visually the trend is more significant during the dry summer period from May to June. This could be an indication toward the climate shift in the area. The other analysis is dependent on the cropping seasons namely Rabi (Wheat growing season for study area) and Kharif (Growing season of cotton crop).

Rabi is the season with less value of the maximum and minimum temperatures starting from October and goes up to March and the Kharif is the warm season spreading from April to September. Kharif cropping season has shown an increasing pattern as shown Figure 4-12 while Rabi season has shown a significant decrease in the visual plot of rainfall anomaly from the mean value over the study period (1978 ~ 2017) given in Figure 4-13.

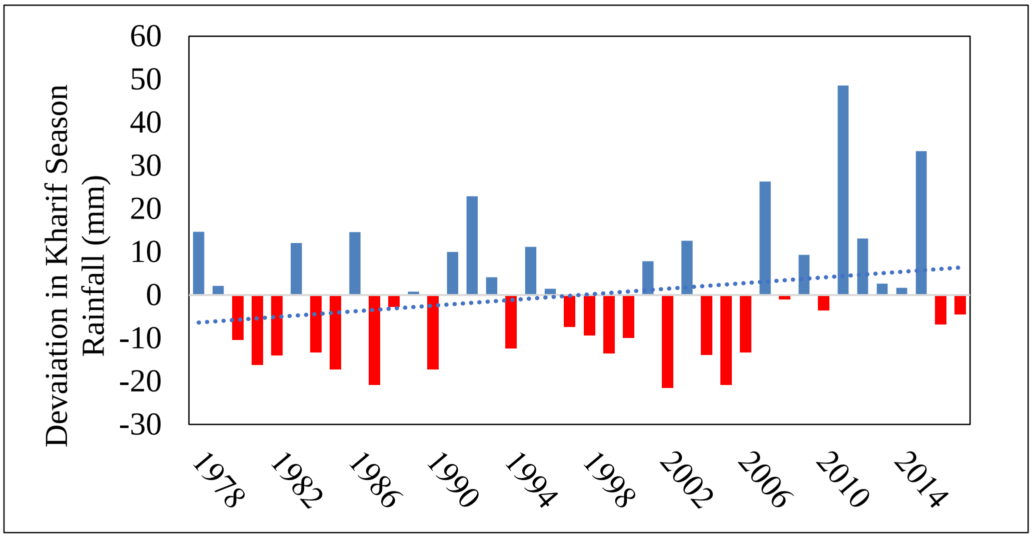


Figure 4-12 Rainfall anomaly in Kharif season over the study period

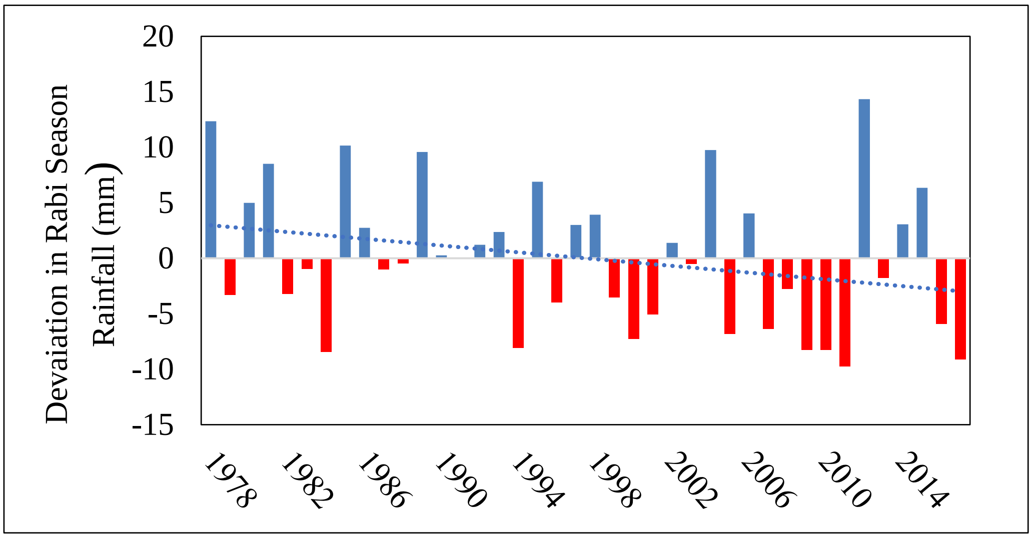


Figure 4-13 Rainfall anomaly Rabi season over the study period

4.6.2 Mann-Kendall and Sen’s Slope test statistics

After analyzing the non-normality of data, Non-Parametric Mann-Kendall test is utilized to analyze the trend within the climate parameters particularly, rainfall and temperature. Table 4-3 is showing the results of the test statistics for annual and seasonal analysis of rainfall data and trends observed for a long-term data series. The test of existing trend is shown at 4 significance levels; i.e. 10%, 5%, 1%, 0.1 %.

Table 4-3 Summary of Mann-Kendall test statistics for rainfall series

Time series	Test Z	Significance level
January	0.5	
February	0.1	
March	-2.8	**
April	-0.2	
May	1.9	+
June	3.4	***
July	-2.4	*
August	0.8	
September	2.5	*
October	-1.0	
November	-1.8	+
December	0.4	
Annual rainfall	0.4	
Winter rainfall (dec-feb)	0.0	
Dry summer rainfall (mar-may)	-1.0	
Monsoon rainfall (jun-sep)	0.6	
Autumn rainfall (oct-nov)	-2.0	*

+ Trend exists at confidence level 90%

*Trend exists at confidence level 95%

**Trend exists at confidence level 99%

***Trend exists at confidence level 99.9%.

After analysing the existence of trend (increasing or decreasing), the linear slope test using Sen’s slope for the magnitude of the trend is also performed. The results of Sen’s slope estimates are shown in the Table 4-4.

Table 4-4 Sen's Slope test statistics for trend

Time Series	Q	Qmin99	Qmax99	Qmin95	Qmax95	B	Bmin99	Bmax99	Bmin95	Bmax95
January	0.0	-0.3	0.5	-0.2	0.3	6.5	19.0	-17.6	14.3	-8.6
February	0.0	-0.7	0.6	-0.5	0.4	11.0	50.8	-19.3	36.4	-9.5
March	-0.6	-1.4	0.0	-1.3	-0.1	49.7	94.6	15.6	85.7	22.3
April	0.0	-0.5	0.3	-0.3	0.2	9.3	34.7	-7.8	27.6	-4.2
May	0.2	0.0	0.7	0.0	0.6	-1.8	7.8	-24.7	6.0	-20.5
June	1.0	0.2	2.2	0.4	1.8	-30.3	9.7	-79.6	-4.3	-64.2
July	-2.0	-4.0	0.1	-3.5	-0.3	171.5	269.2	54.6	248.5	78.4
August	0.3	-0.9	1.7	-0.5	1.3	6.3	77.0	-62.5	48.1	-42.3
September	0.3	0.0	1.9	0.0	1.3	-10.5	3.0	-76.2	1.0	-53.4
October	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
November	0.0	-0.3	0.0	-0.2	0.0	0.0	19.6	0.0	11.0	0.0
December	0.0	0.0	0.1	0.0	0.1	0.4	1.3	-4.6	0.7	-2.8
Annual	0.0	-0.3	0.4	-0.2	0.3	19.5	37.1	1.6	32.7	6.6
Dec-Feb	0.0	-0.4	0.5	-0.3	0.3	8.7	29.2	-12.3	24.1	-4.7
Mar-May	-0.1	-0.5	0.2	-0.4	0.1	18.8	39.3	2.7	32.7	6.1
Jun-Sep	0.3	-0.7	1.3	-0.5	0.9	24.2	71.2	-21.3	61.9	-7.1
Oct-Nov	-0.1	-0.3	0.0	-0.3	0.0	10.1	19.3	2.9	17.4	2.9

The graphical representation for the month of June and Autumn season for Bahawalnagar station is shown in Figure 4-14 and Figure 4-15 for the month where increasing trend in rainfall has been observed.

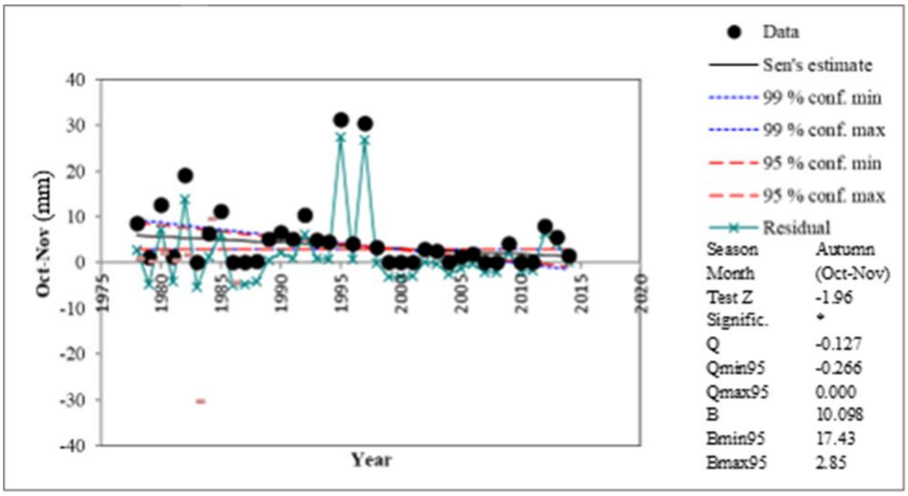


Figure 4-14 Graphical representation of Mann-Kendall and Sen's slope test statistics for month of June

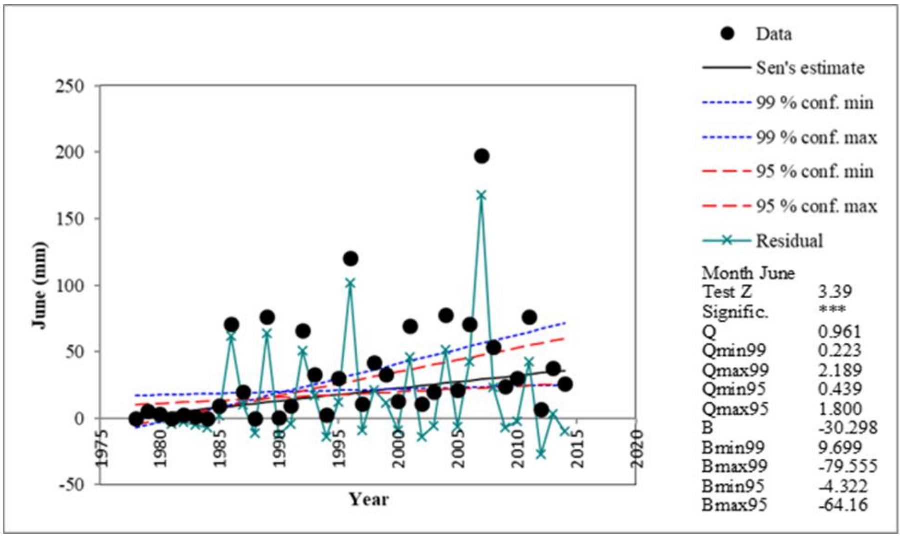


Figure 4-15 Graphical representation of Mann-Kendall and Sen's slope test statistics for Oct-Nov (autumn season)

The Mann-Kendall and Sen’s slope test statistics showed that rainfall of the area has shown significant changes over the period of time. The monsoon season (July ~ Sep) is particularly has shown a shift. July is regarded as the month of highest rainfall but according to the test statistics, it has shown a declining pattern in precipitation while the pattern has shifted to the previous month of June. The other shift is observed in the autumn season (Oct~ Nov) where a continuous decreasing trend is observed while previously the months of winter December to February are recorded as dry with minimal rainfall. Overall annual rainfall of the area did not show any significant change. The reason may be the occurrence of an almost equal number of positive and negative trends that has diminished the overall impact on annual rainfall.

Rainfall of the area is directly linked with the climatic conditions prevailing over the area such as maximum and minimum temperature, wind speed, etc. To evaluate the dependence of rainfall over other climatic parameters, especially temperature, it is essential to analyse their trend as well. We have given due consideration to temperature and rainfall as they are the governing parameters for the irrigation demand as well as climatic conditions of an area. Table 4-5 is showing the trend statistics for the maximum day-time temperature and average annual temperature studied using Mann-Kendall test.

Table 4-5 Summary of Mann-Kendall test statistics for temperature series

	Max daytime Temp (C^o)		Average Annual Temp (C^o)	
Time series	Test S	Sig.	Test Z	Sig.
January	-4		0.8	
February	12		1.2	
March	-8		2.9	**
April	8		1.0	
May	-6		1.9	+
June	-2		0.4	
July	0		2.5	*
August	0		2.4	*
September	20	*	2.3	*
October	10		2.9	**
November	-6		2.9	**
December	8		0.4	
ANNUAL	0		3.4	***
Dec-Feb	9		1.1	
Mar-May	-2		2.5	*
Jun-Sep	2		3.1	**
Oct-Nov	0		3.8	***

The aim is to find the interrelationship of the changing trend of the rainfall with temperature. Graphical representation of test results for annual series is given in Figure 4-16.

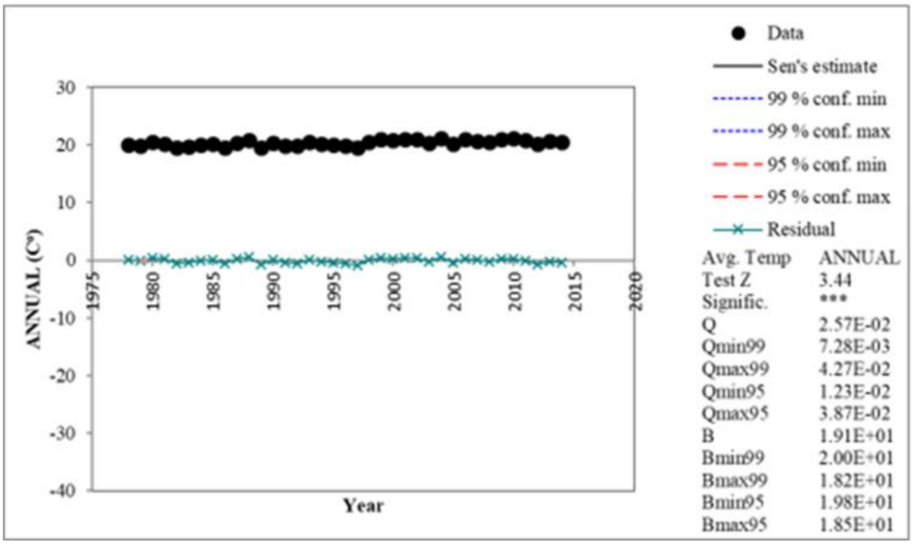


Figure 4-16 Trend analysis of annual temperature for study period

The maximum temperature in September has shown a positive trend that can be directly linked to the increased pattern of rainfall in the month of September. Simply, we can say that rise in temperature has caused the monthly value of the rainfall to increase over the period.

As rainfall has shown significant variation, it is necessary to evaluate the anomaly in terms of some index. For this purpose, the Rainfall Anomaly Index (*RAI*) and Standardized Precipitation Index (*SPI*) have been utilized.

4.6.3 Rainfall anomaly index analysis

In order to access the seasonal dissimilarities of precipitation and to distinguish between the dry and wet periods, yearly Rainfall Anomaly Index (*RAI*) is determined. For this purpose, long-term historic data of precipitation from 1978~2017 for the Bahawalnagar meteorological station nearest to the region of Hakra Canal is utilized. Anomalies are categorized as positive and negative based on a pre-determined average value of precipitation for the long-term data; i.e. annual rainfall value exceeding historic average value of rainfall is dealt as positive anomaly while the one below average value is taken as negative anomaly. An equation developed by Van Rooy (1965) is used for the estimation of *RAI*.

For positive anomalies,

$$RAI = 3 * \left[\frac{\mathrm{N}-\mathrm{N_m}}{\mathrm{M_m}-\mathrm{N_m}}\right] \qquad \text{(Eq.14)}$$

For negative anomalies

$$RAI = -3 * \left[\frac{\mathrm{N}-\mathrm{N_m}}{\mathrm{X_m}-\mathrm{N_m}}\right] \qquad \text{(Eq.15)}$$

where,

M_m= Average of 10 major annual precipitation events of the long-term record (mm),
X_m = Average of 10 least annual precipitations events of the long-term record (mm),
N_m= Mean precipitation per year (mm) of the acquired data series, and
N = Annual precipitation in a particular year (mm).

Calculated RAI intensity values are divided into 7 classes such as Extremely rainy, Very rainy, Rainy, Normal, Dry, Very dry and Extremely dry. The intensity of Rainfall Anomaly Index is classified according to the intensity classes given in Table 4-7.

Table 4-7 Rainfall anomaly index intensity classes (Source: Marcuzzo et al. (2011)

RAI band	**Intensity Class**
>4	Extremely Rainy
2−4	Very Rainy
0−2	Rainy
0	Normal
0− -2	Dry
-2− -4	Very Dry
< -4	Extremely Dry

From the analysis of rainfall data, temporal variations are apparent with dominating numbers of dry years; i.e. Dry, Very dry and Extremely dry during the whole time series under analysis (Table D-1).

In the first decade (1978 ~ 1987), there are five rainy years that occurred on the start of series (1978,1979) and then 1982,1983 and 1986. The highest point of inflection of the dry period occurred in 1985 with *RAI* value of -4.27 classifying it as an extremely dry year. The rainy and dry periods are almost equally occurring in the studied decade. Therefore, the overall time period between (1978 ~ 1987) has an average *RAI* value of -0.47 and classified as dry period but near to normal.

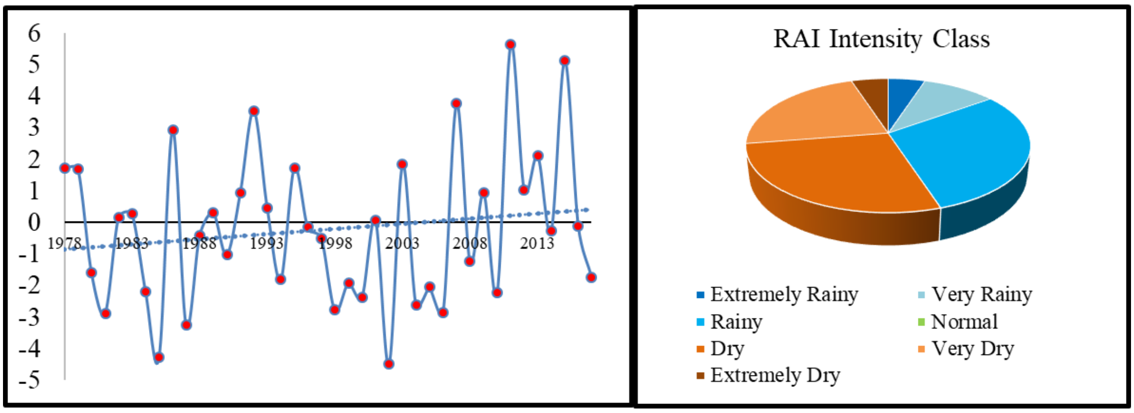


Figure 4-17 Linear trend analysis of annual rainfall anomaly index (RAI)

In the second decade (1988 ~ 1997), the whole period is categorized as rainy with the greatest *RAI* of 3.53 in the rainy year (1992) while the dry year with the highest negative value of *RAI* of -1.82 which occurred in year 1994.

In the third decade (1998 ~ 2007), again the dry period is dominant over the wet period, but the intensity of dryness is high as compared to the first decade of analysis (1978 ~ 1987). In the third decade, the highest dry intensity value is observed as -4.50 in the year 2002 and classified as extremely dry. There were three rainy years one just before and one after the year 2002 and the other one by the end of the decade in 2007 with the highest *RAI* value of 3.76 among the decade.

The fourth and the last decade of observation (2009-2017) is in overall classified as rainy with two extremely rainy years of 2011 and 2015, five dry years occurring in 2008, 2010, 2014, 2016, and 2017. Highest Intensity of *RAI* observed as 5.62 and the least value was -2.22. On average, the whole time period (1978 ~ 2017) of monitoring was categorized as dry with an average value of -0.2 of *RAI*.

4.7 Development of 'abcdm' Hydrologic Model

Bai et al. (2018) insisted to select a catchment that is not exposed to huge influences of anthropogenic activities, particularly on the stream release. This was important because of the objective of the commenced study is to simulate the hydrological response of catchment under the natural climate factors and to verify the impacts caused by climate variability.

Monthly dataset for Kalam station for the period of (1970~1988 and 1993~ 2012) consisting of maximum and minimum temperature, rainfall, and discharge together with watershed outline information with minimal human disturbance is acquired from Surface Water Hydrology Project (SWHP), WAPDA. Monthly potential evapotranspiration (PET) is estimated using the Hamon equation (Cruff & Thompson, 1967). The data scarce condition in the area due to its remote and snow dominant location restricted the use of advanced methods of PET calculation, i.e. Penmen Monteith method, etc., due to nonviability of climatic data such as humidity, wind speed, etc. In data scarce situation, Hamon equation best served the purpose.

A Digital Elevation Model (DEM) of the Kalam catchment has been set-up to draw the catchment boundary and to estimate the elevation variation that is an important factor contributing to snow melt. For this reason, the SRTM (Shuttle Radar Topographic Mission) with 90 m x 90 m resolution was utilized. The downloaded DEM tile, i.e. srtm_51_06, encompasses the whole catchment territory. The delineated catchment has an extent of 2,018 km^2. Mean catchment elevation is from 1,955 m to > 4,500 m a.s.l. Annual precipitation of the area for the recorded dataset is 804 mm in comparison to the historic average rainfall of 910 mm. The traditional split-sample system is applied for model calibration and validation (Bai et al., 2018). The acquired dataset is distributed into three sets of data for warmup, calibration and validation purposes into lengths of 6 years, 16 years and 16 years, respectively. Warmup period data is discarded after stabilizing the model for initial moisture content and groundwater storage values. The aim of stabilizing the model using warmup model was to exclude the influence of initial values in model calibration.

The Pearson Correlation coefficient (r) and R-square (R^2) are used as objective functions to evaluate the model performance, while, Kling-Gupta Efficiency (KGE) and MRAE are used to check the goodness of fit for water resource management. The MRAE is used as an additional measure while KGE is an improved form of Nash-Sutcliffe Efficiency (NSE).

The model was calibrated to match the behaviour of the catchment for the study period of 14 years (1976 ~1992) through the conventional approach of single-criterion optimization; i.e. to maximize Pearson correlation coefficient. Practicable ranges for parameters were specified as follows. Dimensionless parameters a, c, d and m could vary from [0,1]. Parameter b (mm) could change from [0,4000]. Parameter T_{snow} could vary from -5 to 5.

4.8 Model Calibration

After stabilizing the initial soil moisture content and groundwater storage during the model warm-up, the model is calibrated and the value obtained for the optimized parameters are shown in Table 4-6.

Table 4-6 Optimized parameter for model calibration

Parameter	Optimized Parameters	Min	Max
a	0.933	0.873	0.999
b	60.0	0.0	1900.0
c	0.500	0.000	1.000
d	0.000	0.000	1.000
m	1.000	0.000	1.000

Figure 4-18, 4-19 and 4-20 are showing the scatter plot, Normal and semi-log plot for the observed and simulated flows for the calibrated model.

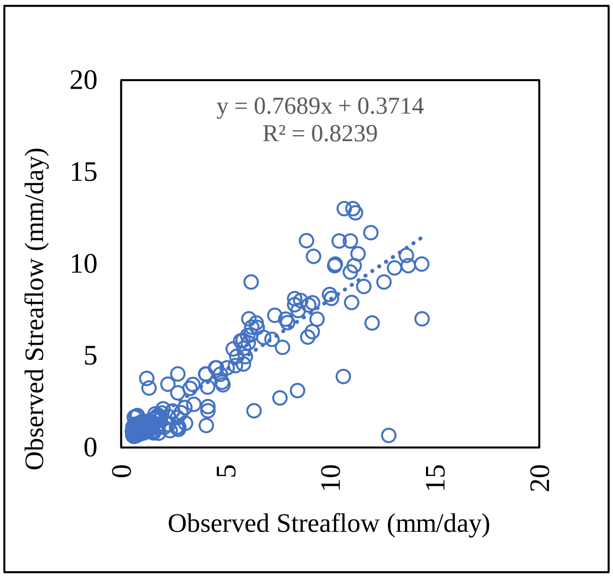


Figure 4-18 Scattered plot for model calibration

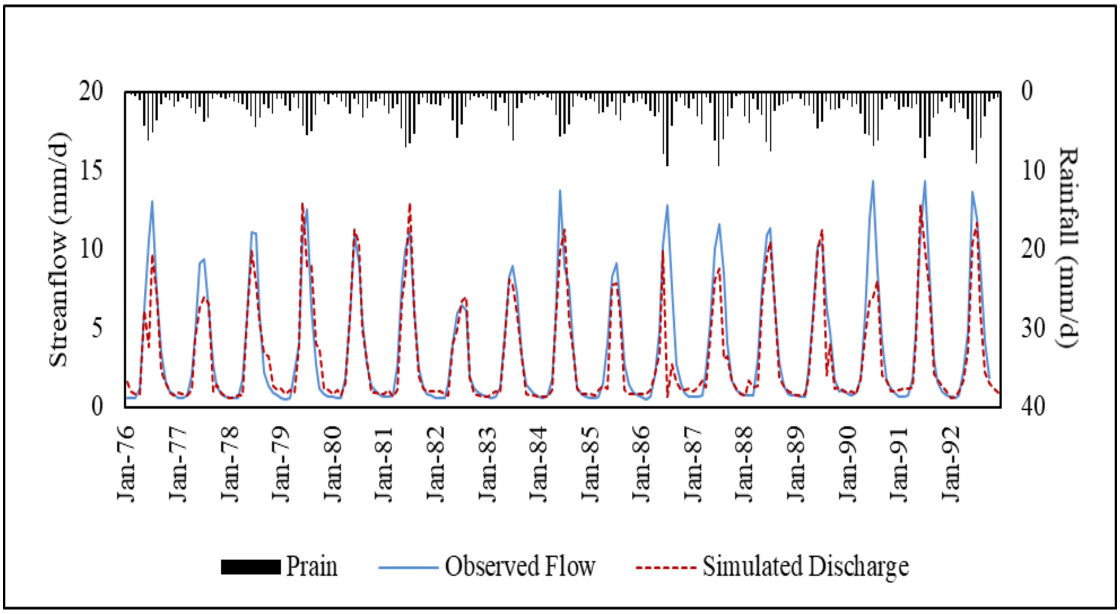


Figure 4-19 Normal plot of observed flow and simulated flow

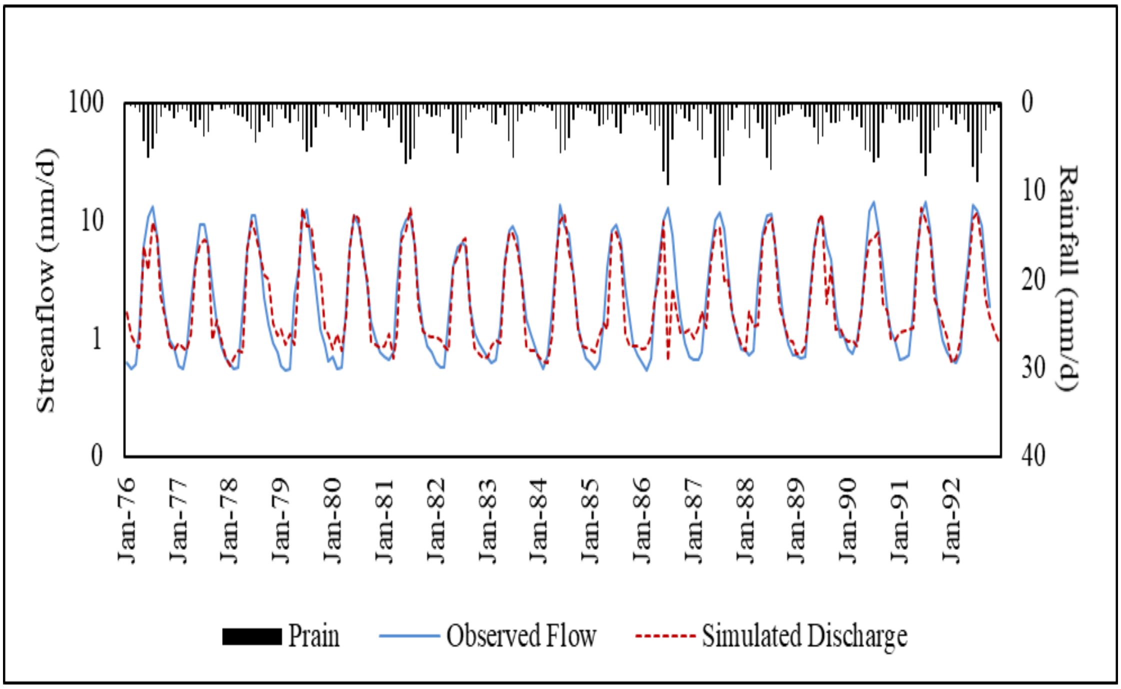


Figure 4-20 Semi-Log plot of observed flow and simulated flow

4.9 Evaluation of Model Performance for Calibration Period

The Evaluation criteria are given in Table 4-7 and MRAE is assessed for checking goodness of fit of model performance. Figure 4-21 is showing the flow duration curve matching obtained for the calibration period. The annual water balance is represented in Figure 4-22.

Table 4-7 Performance Indicators for calibration period

Flow	Pearson	RSQ	MRAE
High flow	0.98	0.96	0.12
Medium	0.99	0.99	0.19
Low flow	0.96	0.93	0.23

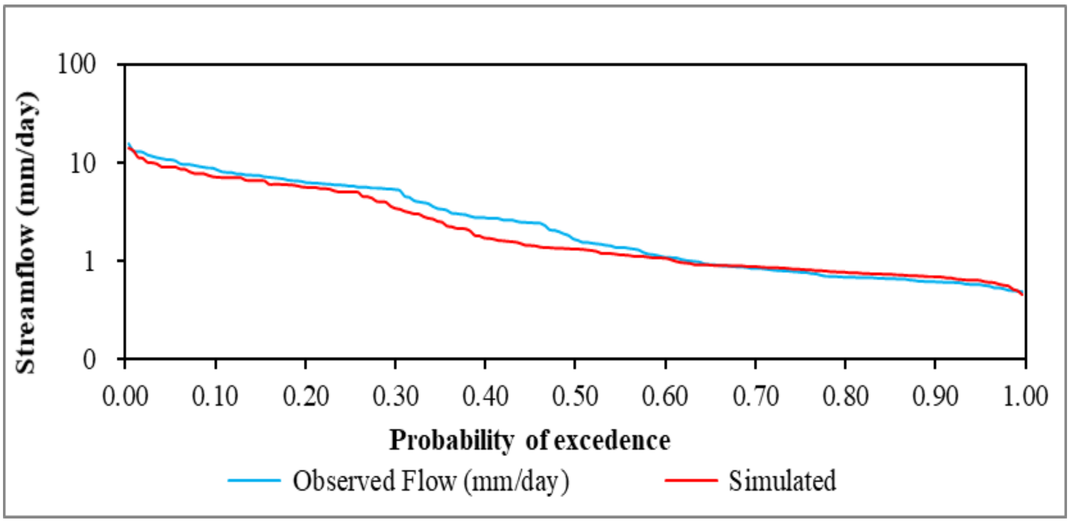


Figure 4-21 Flow duration curve for high, medium, low flows

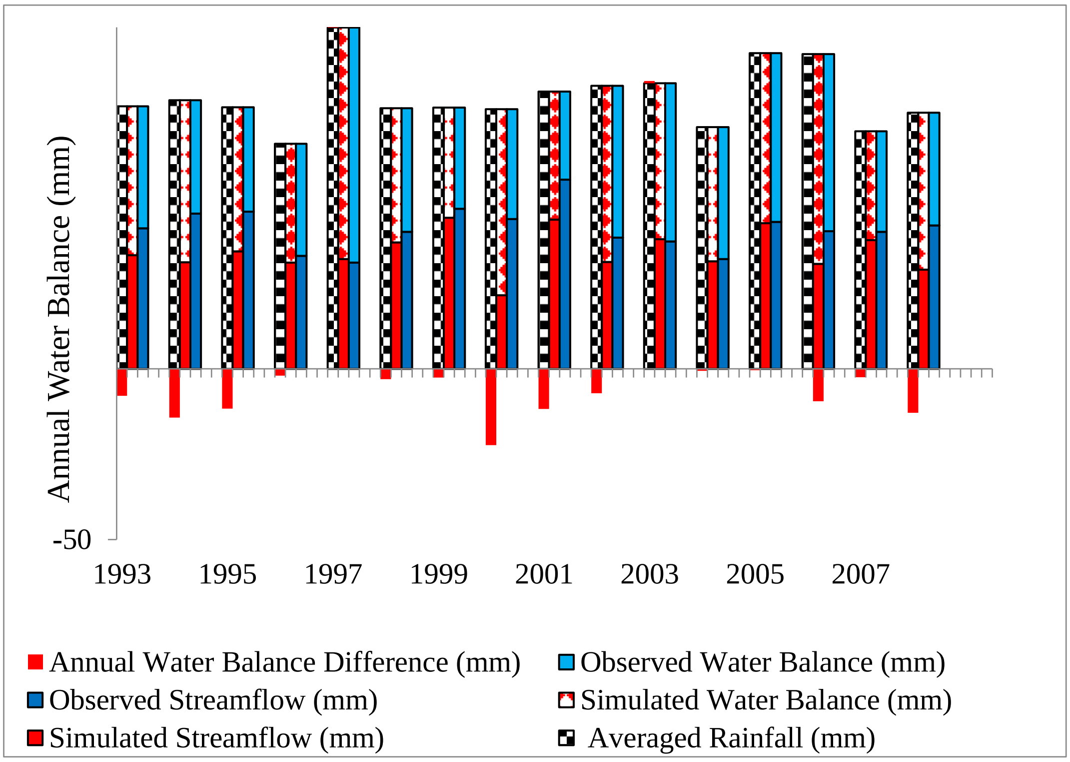


Figure 4-22 Comparison of observed and simulated annual water balance

4.10 Model Verification

The calibrated parameters are used to verify the developed model and to evaluate its performance as shown in Figure 4-23, 4-24, 4-25.

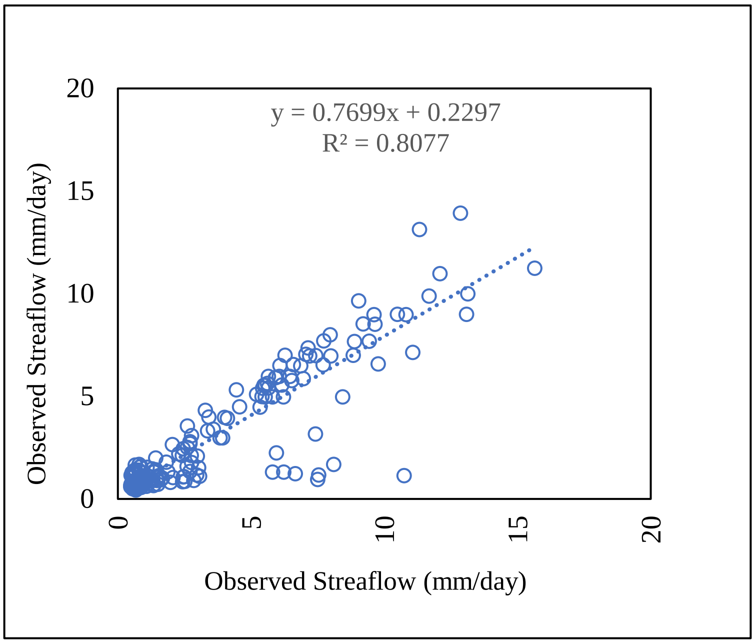


Figure 4-23 Scattered plot of observed flow and simulated flow for the verification period

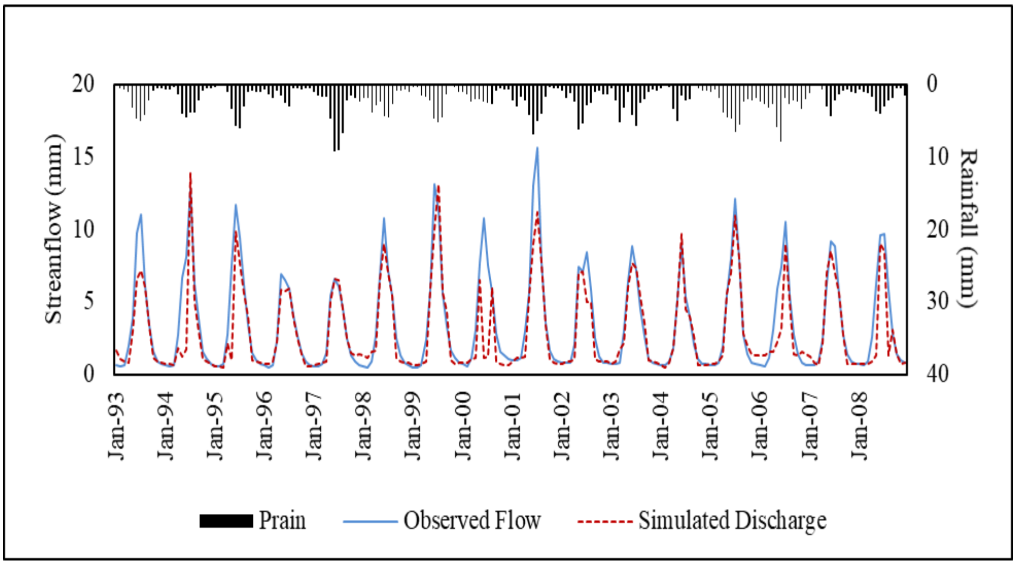


Figure 4-24 Observed flow and simulated flow for the verification period

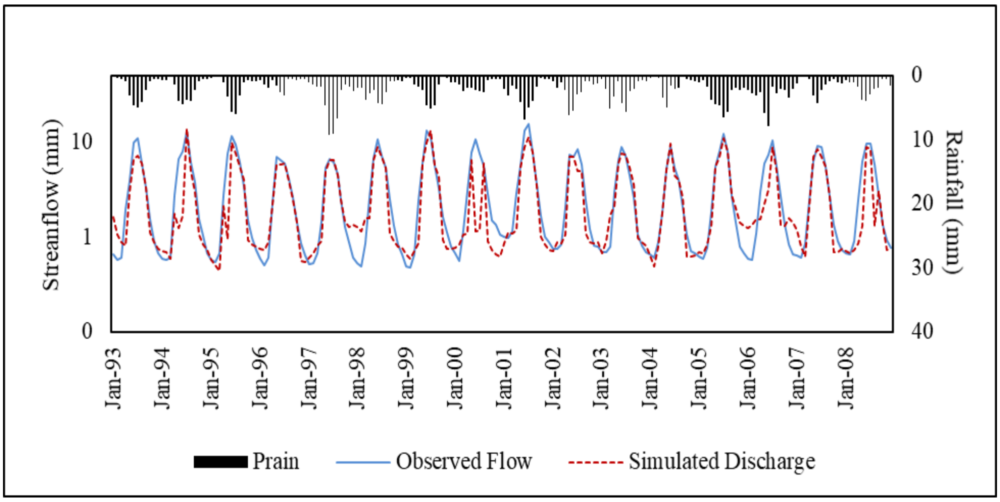


Figure 4-25 Semi-Log plot of observed flow and simulated flow for verification period

4.11 Evaluation of Model Performance for Verification Period

Table 4-8 shows the model performance evaluation for verification period. The flow duration curve graph for the validation period is shown in Figure 4-26. Figure 4-27 is showing the annual water balance for the simulated and observed flow for the validation period.

Table 4-8 Performance Indicators for validation period

Flow Threshold	Pearson	RSQ	MRAE
High flow	0.97	0.94	0.28
Medium flow	0.99	0.97	0.17
Low flow	0.97	0.95	0.09

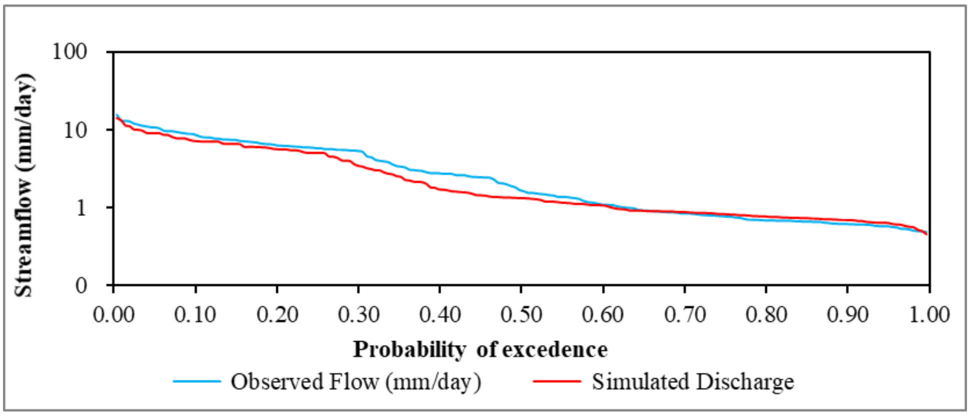


Figure 4-26 Flow duration curve for the verification period

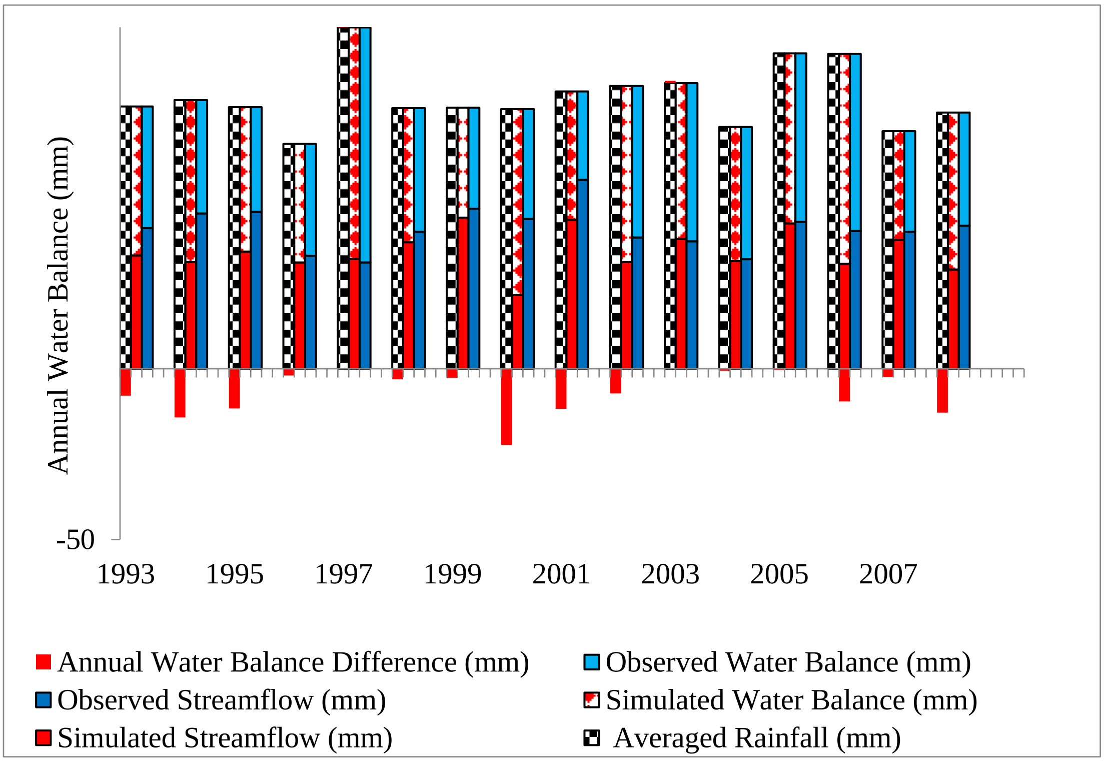


Figure 4-27 Annual water balance for the verification period

5 DISCUSSION

Pakistan is among the most volatile countries concerning the effects of climate variability and change. There exists enormous variation in rainfall from north to south across the country. Sub-northern region of Pakistan receives maximum yearly precipitation in the range of 1,485~1,775 mm that decreases southward and ranges around 37 to 327 mm in south Punjab, Baluchistan and Sindh. The obvious intra-provincial precipitation changes in yearly average precipitation infer the observed climatic gradient across Pakistan.

Water year or hydrological year is used for assessing anomalies in annual and seasonal rainfall. Water year starting from 1st of October to 30th of September of the next year is followed in Pakistan. It is appropriate and preferred to use water year rather than a calendar year as it can best capture the changes in the hydrological cycle by considering all the large events based on the start of simulation time.

5.1 Analysis of Annual and seasonal Rainfall

The outcomes of rainfall analysis of the present study are obeying that settled norm of precipitation increase over the South Asian Region.

The non-parametric analysis of annual rainfall using Mann-Kendall and Sen's slope tests has confirmed the significant increasing trend. For yearly precipitation, the trend has increased from −11.4 mm to −3.3 mm every decade over the investigation time frame. This increasing trend in yearly rainfall is driven mainly by the increase in monsoonal rainfall occurring from July to September and dry summer rainfall that occurs between May and June.

5.2 Analysis of Rainfall Anomaly Index

Years with dry conditions having annual precipitation value less than the historic average have been recurrent in Pakistan in the south-eastern region. Variability in seasonal rainfall is analysed using Rainfall Anomaly Index (RAI). Results of RAI analysis for Bahawalnagar station has illustrated that out of 40, 21 years have shown annual rainfall below average. The dry time frame between 1998 and 2007 matched with the 1998~2002 droughts that occurred in the country and are viewed as the most noticeably awful for the past 50 years. The dry season began in 1997 as El-Nino grew, yet the dry spell picked up power in 1998 and achieved its peak in 2000 and then gradually weakened as shown by low RAI values (Table 5). Dry season enduring quite a while is regular since these occasions have longer time scales and may reach out for a considerable length of a decade even (Santos, A. B. M. et al., 2018).

From the annual analysis of Rainfall anomaly index, it is apparent that area is classified as dry because it is dominated by the dry period most of the time in the observation period.

Even with the significant increase in annual rainfall, it is still not adequate to fulfil the irrigation requirements, i.e. 2,690 mm vs. 1,600 mm annually. Current contribution of rainfall is only around 13% in the total irrigation supplies. Despite the annual increase in rainfall, the decadal rainfall is highly variable and cyclic in manner. Each dry decade is likely to be followed by a wet decade, but the intensity of wetness is comparatively reducing.

5.3 Disparity between Rainfall and Actual Water Requirement

As with most of the canals in Pakistan, such as Eastern Sadiqia Primary Canal that is the source of water to Hakra canal, gets water directly from Sutlej river and so the discharges in canal fluctuate with the releases from the river. The similar fluctuation pattern is observed in the estimated deficits over the past ten years.

The seasonal comparison of the water availability and water requirement for the past 10 years reveals that the major deficit in water supplies in the Rabi season is ranging from 7% to 26% in different years. The minimum deficit is observed in the year of 2010. In 2010, the flood occurred in most parts of the country thus improving the river flows that resulted in a lower disparity between actual requirements and available canal flows.

However, overall there is a shortfall of 73% in Kharif season on average. The maximum water deficit observed in the driest year ranged up to 78% with the minimum value of 71%.

On an annual basis, the gap between the actual canal water supplies and crop consumptive use reduces to 63% in comparison to the actual water availability for the past 10 years (2008~2017). Seasonally, the average value of shortfall between supplies and demand is 19% and 73% for Rabi and Kharif seasons, respectively.

Inherent shortfall of supply is not adequate to fulfil the irrigation demands along with the cultivable acreages of the distributaries. Subsequently, the canal framework is worked or operated on a roster system where the opening and closure of specific distributaries happens accordingly. Roster plan is designed in such a way that when a distributary is operational, it can carry discharge as per its design capacity. The objective is to ensure the non-silting, non scouring velocity and to deliver the water to adjacent fields by providing an appropriate elevation within the channel.

5.4 Groundwater Estimation Verification

The analysis of the Hakra canal system indicates that area is under serious water stress especially in the cotton (Kharif) growing season that is the cash crop of the country. To overcome these shortfalls, farmers make use of groundwater. For the study area, analysis of the estimated groundwater abstraction shows that maximum water is extracted in the month of May which is approximately 84% of total irrigation requirements, while the minimum contribution from the groundwater is taken in the month of February with an average value of around 20%. September is the month that has shown the recharge potential to the groundwater through the data analysis period (2008~2017) with the higher availability to demand ratio. However, any governmental authority is not responsible for groundwater abstraction and it is exclusively the farmers who extract the requirements on their own cost by digging up the shallow wells. The analysis of the groundwater depth from the surface for the study canal is analysed for the period of (2009~2017). The depth varies from 2.76 m to 3.54 m for Hakra canal. The estimated mean values of groundwater abstraction for each year are evaluated against the groundwater depth and it has been found that there exists a strong correlation between the groundwater depth to the groundwater contribution. During the study period, the years with higher groundwater contribution has shown the increasing trend in their groundwater depth from the surface (drawdown). However, the groundwater monitoring data is limited as the groundwater monitoring started by the Irrigation Department only after 2008 and it is recorded only twice a year before and after the monsoon season. This is a limiting factor for any detailed study as it does not provide the indication of true seasonal or annual variations.

The contrasts between the allocated quantity of water and the water that reaches to the canal are not only resulted due to variabilities in river inflows and precipitation from year to year but also due to insufficiency of estimation, management practices and operational strategies to minimize this difference.

Establishment of rotational plans, with the double objectives of minimizing inequity and minimizing the contrast between canal capacity and operational availability based on robust algorithms or hydraulic models, must be carried out. This is often of specific significance for those canals belonging to the lowest priority subset within the rotational plan.

For the Hakra canal command area, the water allowances are recommended to be improved especially for the Kharif season. It is needed to discourage the extraction of high groundwater by designing better water management and conservation practices.

5.5 Climate Variability in the Indus Basin

Climate variability in the study area for the data period (1978 ~ 2017) is evaluated. Climate examination is required to portray the inconstancies in the climate of recent 4 decades to help highlighting of the variables driving functionating in the available supplies to the command area of Hakra canal. The trend analysis of the precipitation data supported the argument of climate variability within the study area. Perception trend analysis is conducted on monthly, annual and seasonal basis. Mean annual rainfall of the area does not follow a specific trend as observed from the Mann-Kendall and Sen’s slope tests. But there are significant climatic variations within the monthly and seasonal rainfall, such as rainfall in the hot month of June has shown a remarkable increasing trend with the z-value of 3.39 in Mann-Kendall test at 5% confidence interval while the Sen's slope gives positive slope even at 0.01 significance. Therefore, the increasing trend seems to be more likely with Sen's slope method. Similarly, an increasing trend is also observed in September, the ending month of the monsoon season at a significance level of 0.05. The increasing trend is comparatively weak as the Sen's slope almost diminishes by the end of the trend and the residual points are also not random, so here the Mann Kendall test is the best indicator of an increasing trend. Rainfall of the area has shown a decreasing trend in autumn season (Oct-Nov) following monsoon season. The main contribution to this decreasing pattern is observed due to the decreasing pattern in the rainfall of November month. October~ November is the cultivation season for the wheat crop. At the initial stages of the growth, the crop requires more water therefore the reduction in rainfall would create more stress over the irrigation requirement.

Evaluation of other climatic factors such as temperature and evaporation are also carried out. The maximum daytime temperature of the area has shown an increasing pattern, but it is not significant as tested from non-parametric tests of Mann-Kendall and Sen's slope. A significant increasing monotonic trend on the significance level of 0.05 is observed in the month of September. The precipitation evaluated depicted an increasing trend in the same month over the past four decades may be attributed to this rise in temperature. Subsequently, the month of June has also shown a positive trend and November has shown a negative trend but when tested with the Sen's slope test, the results were insignificant as the increase or decrease in rainfall value is found to be linked with the temperature of that specific month or season. Hence, it can be concluded that for the study area, the temperature is the major contributing factor for rainfall variability while doing the examination of the variability of the minimum night-time significant temperature variations are observed in the month of January and November. Month of November has shown a declining trend in the minimum temperature while January has shown an increase in minimum temperature. Minimum temperature evaluation has also revealed the significant increase in minimum temperature on an annual basis even on the significance level of 0.01. Average annual temperature of the area has shown a positive slope even at a confidence level of 99.9%. It is verifying the monotonic trend observed by the Mann-Kendall test. A slight increase in temperature even of 0.1-0.5 ^{o}C cause the production of crops to be adversely impacted (Drop of 1-5%in yield), especially rice.

The variability in climatic factors like in precipitation and temperature along with other climatic components may impact the reference evapotranspiration and consequently, the crop evapotranspiration or consumptive use of crops as well. It would elevate the maximum soil moisture deficit that results in crop failure or low yield. Although, the trend does not appear during the Mann Kendall test for reference evapotranspiration values of the area, but when it is assessed for the specific month of November as the precipitation decreases and temperature increases, it has been observed for that particular month, a strong relationship can be seen between the three climatic factors as shown in the results. For a country like Pakistan whose major economy is relying on agriculture, this changing climate would be a dual challenge together with the inherent water scarcity.

Snow cover regions got to be measured appropriately arrange to estimate and figure out the runoff from locales such as upper Indus basin, but there is a lack of comprehensive and in-detail data about of ice and snow forms and their relationship with the hydrological administration in this locale. In-situ information is restricted to lower and available elevations and may not genuinely speak to the snow and ice sheet changes in the long run.

6 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

The average temperature in the Hakra Canal has increased from an average value of 25.43° C to 26.15 ° C over the time period of the last 40 years. The decade from 1998 to 2007 is regarded as the hottest decade with an average annual rise of 0.07 ° C in average temperature.

Average annual increase of 0.07 °C may be attributed to critical decline in the Himalayas snow spread. At present, snow cover is one of the foremost critical factors that can be acclimated in the light of water resource management.

Increase in temperature has caused the excessive use of groundwater for irrigation in case of lower supplies through the canals. An increasing trend in groundwater abstraction is observed for the study period of 2009-2017. Maximum abstraction took place in the year 2013 and it was around 40 % of the total irrigation requirement.

Groundwater abstraction continuously increases from March to May and reaches the extreme value of 12 mm/d in May. Month of September has shown a positive value or in other terms, a recharge is observed in that particular month. The shortfall between the demand and supply from the upstream sources is averaged as 63%. This shortfall can further worsen due to population explosion and climate variability.

Catchments having consistent snow cover round the year provide flexibility in hydrological modelling making the modlling process rather smooth than the catchments having inconsistent snow cover. Hydrological modelling of the selected upper catchment in IBIS was therefore little hard to perform due to highly fluctuating snow cover round the year.

The Pearson correlation coefficient for medium flow has shown a value of 0.99 that depicts that the model is accurately imitating the hydrological behaviour of the catchment. The validated model can be effectily utilized to predict the behaviour of hydrogical processes and consequent changes availability of irrigation supply in the downstream of the basin.

Medium flows originating from the catchment are of prime importance as the agricultural productivity in the downstream of IBIS is strongly dependent on the water resource management in the upstream.

The variability in the climatic parameters in the downstream is validated by the change in hydrological behaviour such as change in snow melt behaviour and quantity of runoff produced in the upper catchment. To have some sensible level of certainty that the model can give hydrologically steady simulation of catchment conduct, it is likewise important to look at water balance of the catchment.

Unreliable supply of water in the IBIS system would disturb the dynamics of hydrological water cycle hampering crop yield.

6.2 Recommendations

Water allocations for the system have to setup on impartial basis and progress around there is conceivable if the IWRM standards are applied and executed. Currently the average system efficiency is considered as 42.5%.

The tremendous water system frameworks of the Lower Indus additionally need to adjust to the future changes. For instance, substantial loss of canal water both during movement and application can be essentially diminished through better lining of the channels and enhanced water management on form as the system discharge is measured using so-called KD formula. Lining of the channel would significantly impact the correct estimation of discharge.

The ‘abcdm’ has shown reliable results for the intermediate and low flows. Thus, the model can be used effectively for the modelling of flows for estimating climate variability impact on streamflow. Assumption for the T_{rain} and T_{snow} are highly place specific, so need to be consulted with literature and ambient conditions prior to application of model if the snowmelt volume is not already known.

Climate is changing as the precipitation and temperature analysis of the area has shown variability over the study period of 1978~2017 and so as the stress over the various water sectors such as agricultural demands which would increase. There is a need to see climate change in snow prone areas and relate it to the dependant areas.

Relating climatic variability on a special scale is an effective approach for the data scarce areas.

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ANNEX A – DATA

Table A - 1 Summary of missing data and replacement method

Data Type	Treatment Method	Temporal Resolution	Reference(s)	Remarks/Limitations
Hydrological Data Meteorological Data	Deletion Method i.e. Listwise deletion Pairwise deletion	Daily/ Monthly	(Elshorbagy et al., 2000) (Lang & Little, 2016)	For the data with no significant pattern and considerably long segment of data are missing.
Rainfall Data	Normal Ratio method	Daily	(Caldera, Piyathisse, & Nandalal, 2016)	Neighbouring station with low corelation factor. Normal annual rainfall of neighboring station exceeds 10% of the nomral annual rainfall of target station.
Rainfall Data	Series Average/ Interpolation Method	Daily/ Monthly	(Elshorbagy et al., 2000) (Caldera et al., 2016) (Bastin, Lorent, &	Neighbouring station with annual average rainfall within 10% of normal rainfall of traget/index station.

Data Type	Treatment Method	Temporal Resolution	Reference(s)	Remarks/Limitations
			Gevers, 1984) (Chow et al, 1988).	Data must be few and sparingly distributed.
Rainfall Data/ Weather Data/ Streamflow Data	Closest Station Method	Daily/ Monthly	(Garcia et al., 2006) (Elshorbagy et al., 2000) (Eichert, 1982)	For daily in filling the % of missing data must be low for reasonable results.
Rainfall/ Stream flow	Regression method i.e. Linear Regression method Weighted Linear Regression method,	Daily/ Monthly	(Elshorbagy et al., 2000) (Caldera et al., 2016)	Neighbouring station with very high corelation factor

Data Type	Treatment Method	Temporal Resolution	Reference(s)	Remarks/Limitations
Water Resources Data/ Rainfall Data	Multiple Imputation	---	(Dong & Peng, 2013) (Little & Rubin, 1989) (Tabachnick & Fidell, 2013) (Lang & Little, 2016)	Missing data following MAR mechanism gives valid result using MI technique. Data violating normality can even be best treated by multiple imputation technique.
Rainfall Data/ Other than water resources	Artificial neural networks (ANNs)	---	(Elshorbagy et al., 2000) (Wan Ismail et al., 2017)	Promising Results are obtained in water resources and other fields.

ANNEX B – ANALYSIS

Table B-A Annual precipitation and rainfall anomaly index (RAI) of the Bahawalnagar, Punjab, Pakistan between 1978 and 2017

Water Year	Precipitation (mm/ year)	*RAI*	Intensity Class
1978-1979	146.4	-2.33	Very Dry
1979-1980	119.9	-2.78	Very Dry
1980-1981	81.8	-3.44	Very Dry
1981-1982	83.9	-3.40	Very Dry
1982-1983	346.1	0.98	Rainy
1983-1984	60	-3.81	Very Dry
1984-1985	77.8	-3.51	Very Dry
1985-1986	143	-2.39	Very Dry
1986-1987	124.9	-2.70	Very Dry
1987-1988	268.6	-0.23	Dry
1988-1989	389	1.64	Rainy
1989-1990	267.7	-0.24	Dry
1990-1991	612.8	5.08	Extremely Rainy
1991-1992	592.6	4.77	Extremely Rainy
1992-1993	469.1	2.87	Very Rainy
1993-1994	291.8	0.15	Rainy

1994-1995	537.5	3.92	Very Rainy
1995-1996	435.4	2.35	Very Rainy
1996-1997	324.5	0.65	Rainy
1997-1998	369.7	1.35	Rainy
1998-1999	166.7	-1.98	Dry
1999-2000	225.9	-0.96	Dry
2000-2001	296.5	0.22	Rainy
2001-2002	96	-3.19	Very Dry
2002-2003	323.4	0.64	Rainy
2003-2004	187.4	-1.62	Dry
2004-2005	139.2	-2.45	Very Dry
2005-2006	246	-0.62	Dry
2006-2007	411.2	1.98	Rainy
2007-2008	263.8	-0.31	Dry
2008-2009	289.2	0.11	Rainy
2009-2010	231.1	-0.87	Dry
2010-2011	507.6	3.46	Very Rainy

2011-2012	292.5	0.16	Rainy
2012-2013	250	-0.55	Dry
2013-2014	351.7	1.07	Rainy
2014-2015	450	2.58	Very Rainy
2015-2016	243.5	-0.66	Dry
2016-2017	279.6	-0.04	Dry