EFFECT OF CLIMATE CHANGE ON CROP WATER REQUIREMENT USING CMIP6 DATA OVER PAKISTAN

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My beloved father & mother

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ABSTRACT

In recent years, there has been an increased focus on studying the impact of climate change on crop water requirements (ETc), specifically evapotranspiration, due to the effects of temperature and precipitation variability. While many studies have projected long-term scenarios, there has been a lack of short-term predictions, particularly for a 10-year period, in the existing literature, specifically for assessing crop water requirement (ETc) in Pakistan. This thesis aims to address this gap by utilizing short-duration projected data from the Decadal Climate Prediction Project (DCPP) obtained from the Coupled Model Intercomparison Project Phase 6 (CMIP6) repositories. The objective is to assess the impact of climate change on crop water requirements across the provinces of Pakistan, focusing on the cotton and wheat seasons. To analyze ETc variations attributed to climate change, the study employed the CROPWAT 8.0 software, based on the guidelines provided by the Food and Agriculture Organization (FAO). Results revealed that IQ Range of ETc for the cotton season in Sindh and Balochistan exhibit higher scattering and more erratic behavior compared to Punjab and Khyber Pakhtunkhwa (KPK). The higher IQ Range values in Sindh (8.3 mm/Dm) and Balochistan (3.6 mm/Dm) contribute to this pattern, while Punjab and Khyber Pakhtunkhwa show a more consistent behavior with lower IQ Range values (1.65 mm/Dm and 0.9 mm/Dm) respectively.For the wheat season, the IQ Range analysis of ETc indicates that Sindh displays a higher scattering of anomaly data compared to Punjab, Khyber Pakhtunkhwa , and Balochistan. The higher IQ Range value in Sindh (0.9 mm/Dm) suggests significant variations and erratic behavior of ETc anomalies. In contrast, Punjab, Khyber Pakhtunkhwa , and Balochistan exhibit a more consistent pattern, with their ETc anomalies closer to the median values and lower IQ Range values (0.2 mm/Dm, 0.3 mm/Dm, and 0.3 mm/Dm) respectively, indicating a more stable ETc pattern. The study revealed significant findings regarding the projected changes in crop water requirement (ETc) in different provinces of Pakistan during the cotton and wheat seasons. Sindh exhibited the highest increase in ETc during the cotton season, with a mean anomaly of 1.8 mm/Dm and a standard deviation (StDev) anomaly of 4.6 mm/Dm. Punjab displayed high variability in ETc anomalies during the cotton season, with the highest StDev observed. Balochistan showed an increase of more than 0.4 mm/Dm in evapotranspiration rate for the cotton season, with a StDev of 2 mm/Dm. In contrast, Khyber Pakhtunkhwa experienced a decrease in ETc anomalies for both seasons. These findings have significant implications for water management strategies in the respective regions.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATION

CDF	Cumulative Distribution Function
CMIP	Coupled Model Intercomparison Project
CRI	Crown Root Initiation
ETc/CWR	Crop Water Requirement
DCPP	Decadal Climate Prediction Project
DP	Deep Percolation
DTR	Diurnal Temperature Range
ER	Effective Rain
ESGF	Earth System Grid Federation
ET	Evapotranspiration
IPCC	Intergovernmental Panel on Climate Change
IQ	Interquartile
IR	Irrigation Requirement
WCRP	World Climate Research Programme
TAW	Total Available Water

LIST OF APPENDICES

CHAPTER 1

1. INTRODUCTION

1.1 Climate Change:

A region's climate may be defined as the atmosphere's conditions over a long period of time, usually 30 years. The many meteorological features and their variations make up climate. The main components of current global climate change scenarios are temperature, precipitation, and variability. One crucial aspect of a location's climate is the degree to which rainfall amounts vary over time or within a given area. Common measurements of variability, such as the standard deviation, may be interpreted for climate and weather research utilising the underlying premise of a standard normal distribution (Masson et al., 2020)

Climate change is described as a long-term statistical shift of climatic variables in a specific area or throughout the globe that is persistent and, in some situations, irreversible. Modern climate change appears to be primarily driven by an increase in atmospheric quantities of greenhouse gases. The effects of CO2-induced climate change, which have already had an impact on a number of global businesses, are expected to become more obvious over the next several decades, with long-term ramifications for many industries. Because of this, assessments of the global and regional effects of climate change are grabbing the interest of various academic communities and stakeholders (Dingle & Stewart, 2020).

The only topic covered in climate change discussions and programs up to this point has been GHG mitigation (Dingle & Stewart, 2020). Despite widespread and persistent calls from poor countries for a greater emphasis on adaptation methods, adaptation-related provisions of climate change plan policies have only recently started to get significant consideration in climate change treaties and negotiations. (Addisu et al., 2015; Masson et al., 2020)

1.2 Climate Change Parameters:

1.2.1 Precipitation:

In dry regions, precipitation is a crucial component of the water cycle. Food and water availability in dry and semi-arid environments are impacted by a lack of precipitation. Humans are the most impacted by changes in weather extremes brought on by climate change. Temperature variations are a big additional source of worry (Sharma & Goyal, 2020).

Water availability for hydrological and agricultural purposes across time is described by the Mean Annual Rainfall Pattern (MARP). In rain-fed conditions, it reduces a region's capacity for sustainable agriculture. For scientific reasons as well as to better restrict expected global and regional changes, it is crucial and continuing study to understand for scientific reasons and to better restrict expected global and regional changes (Adnan et al., 2020; Ostad-Ali-Askari et al., 2020).

1.2.2 Temperature:

As a measure of the average kinetic energy of particles in a specific material, the temperature is frequently defined as the degree of hotness or coolness of a body or environment. A meteorological observatory measures the air temperature every synoptic hour. In determining a region's climate and atmosphere, it is important to consider the daily mean temperature, lowest temperature, and daily maximum temperature (Harvey et al., 2020).

The difference between daily high and low temperatures is known as the diurnal temperature range (DTR), which is frequently cited as a sign of climate change. Daily changes in maximum temperatures are crucial throughout the summer because they have a significant and immediate impact on the ordinary individual (Shah & Ahmad, 2017; Sharma & Goyal, 2020).

1.3 Crop Water Requirement as a Concept:

The crop’s water need is the amount of water needed in-depth (or volume) to make up for water lost through evapotranspiration. In other words, it is the amount of water needed for various crops to grow and thrive to their fullest potential (Ali & Ali, 2010). When anything is referred to as a "crop," it always refers to a crop that is grown in a perfect environment, such as one that is uniform, actively growing, completely shading the ground, free from disease, and in healthy soil (including fertility and water). The crop, therefore, yields at its highest possible level in the environment. (Amin et al., 2022; Haider & Ullah, 2020).

Plants need more water per day in sunny, warm climates than they do in gloomy, frigid ones, which is a significant consequence of climate. How a harvest is made Millet and sorghum require less water throughout the growing season than do maize and sugarcane, while mature crops need more water than those that have just been planted. (Chakravarti et al., 2022; Yassen et al., 2020).

Crop water requirements (ETc) are the quantities of water required at a given period to make up for evapotranspiration losses from a cultivated area. For management purposes, such as anticipating irrigation water demands, scheduling irrigation, and scheduling water deliveries, crop water requirements are typically represented in millimetres per day, millimetres per month, or millimetres per season. (Casolani et al., 2020; Ewaid et al., 2019).

Crop evapotranspiration and crop water needs are intricately related since both phrases refer to the same amount of water. There are some differences between them, though. While crop evapotranspiration represents actual water losses (i.e., a hydrological word), The amount of water that should be provided to make up for these losses is determined by crop water needs (i.e., an irrigation management term) (Moseki et al., 2019). The effective irrigation water supply needed for maximum productivity is represented by this amount of water. As a result, estimating crop evapotranspiration comes before estimating agricultural water needs, with the latter frequently reflecting values of crop evapotranspiration averaged across time. (Chakravarti et al., 2022; Govere et al., 2020) .

The amount of irrigation water effectively applied to the root zone and the effectiveness of precipitation satisfy the crop's water requirements. The relevance of agricultural water requirements increased as a result of the need to forecast the water quantities to be provided to newly irrigated regions due to the building of substantial engineering works (Surendran et al., 2015). In general, it is possible to distinguish between crop water requirements for real-time management, where the current season's climatic data are used and crop water requirements for long-term planning, where a typical climate or one with a certain probability of occurring can be used for E estimation. (Chakravarti et al., 2022; Masia et al., 2021).

1.3.1 Major Factors Affecting Crop Water Requirement:

1.3.1.1 Climate Factor:

In comparison to a crop cultivated in a cloudy, colder climate, a crop grown in a sunny, hot climate needs more water each day. Crop water requirements are influenced by a number of climatic factors, in addition to sunlight and temperature as shown in figure 1.1. These two components are wind speed and humidity. Crops require more water in dry environments than they do in humid ones. Crops will need more water in windy conditions than in calm conditions (Neenu et al., 2013).

Hence, hot, dry, windy, and sunny locations have the highest crop water requirements. When it is frigid, wet, dreary and with little to no breeze, the levels are at their lowest. It is obvious that the water needs of crops grown in various climatic zones would vary (Vogel et al., 2019). As an illustration, a certain type of maize grown in a colder climate will use less water per day than the same variety grown in a hotter climate (Liliane & Charles, 2020).

Table 1.1 Effect of major climatic factors on crop water needs.

Climatic factor	Crop water need	
	High	**Low**
Sunshine	Sunny (no clouds)	Cloudy (no sun)
Temperature	Hot	Cool
Humidity	Low (dry)	High (humid)
Wind speed	Windy	Little wind

The specific climate for sowing crops also has an impact. Summer evaporation is greater than winter evaporation, hence summer-planted crops require more water than winter-planted crops. Likewise, the level of humidity influences water demand. Demand for water declines during rainy seasons. Winds offer evaporation with velocity. Less wind will diminish demand. The duration of the day and whether the sun's rays are direct or indirect also affect water demand. Higher temperatures will increase evaporation, which will raise water consumption (Neenu et al., 2013).

1.3.1.2 Impact of Crop Type on Crop Water Requirement:

Duties are also required since various crops require different amounts of water to mature. The duty would be proportional to the crop's water requirement. The impact of crop type on agricultural water requirements is significant in two ways. **A.** Crop type determines the daily water needs of a fully matured crop; for example, a fully established maize crop will require more water per day than a completely developed onion crop. **B.** Crop type determines the length of the crop's overall growth season (Liliane & Charles, 2020; Muzammil et al., 2020).

Varying crops require different amounts of water. For example, rice and sugarcane require more water, whereas bajra and jowar require less. Water demand is also determined by crop length and growth stage. Long-duration crops require more water, but short-duration crops require less. Water demand is also affected by plant development (Kaushika et al., 2019). Plants, for example, require less water in their early stages and more water during their growth phase. Water requirement is also influenced by the structure of plant roots. The deeper the roots, the more water they hold (Pereira et al., 2021; Ye et al., 2015).

1.3.1.3 Influence of Soil Type on Crop Water Requirement:

The capacity of the soil to retain water is determined by its composition and compaction. Crops grown in sandy soils require more water due to higher infiltration rates (Tomaz et al., 2020). Similarly, topsoil requires more water than deeper soils. The amount of water required by plants is directly determined by soil fertility (Liliane & Charles, 2020).

Evaporation is greater in soils with lesser fertility. Water discharge in various types of soil also has an impact on its status; in saturated soils, plants use less water due to decreased evaporation. Plants require less water in circumstances of defective water outflow (Purakayastha et al., 2019).

1.3.1.4 Influence of Water Table on Crop Water Requirement:

Pakistan’s freshwater resources are under pressure due to the country’s constantly growing population’s rising demand for food and fiber. Optimal use of surface and groundwater resources is now essential to closing the water supply-demand imbalance. 18 3.05 m 3.05 m 6.1 m deep lysimeters were constructed in Lahore, Pakistan, to study the impact of shallow water tables on crop water needs. Many crops were tried, including wheat, sugarcane, maize, sorghum, berseem, and sunflower. These tests’ results showed that the contribution of groundwater to agricultural water needs varied with water-table depth. At 0.5 m deep, groundwater supplied all the water needed for wheat, but more than 80% of the water needed by sunflowers was absorbed by the soil (Gou et al., 2020).

It was found that sensitive crops like sorghum and maize were waterlogged and that yields dropped as the water table increased. The water table has to be at or below 2.0 m in depth, though, to provide the highest sugarcane production. All of the crops examined, in general, were shown to perform best at a water-table depth of 1.5–2.0 m. The existing irrigation supply and water allowance system have to be changed in areas with shallow water tables to reduce over-irrigation and wasteful water consumption (Liliane & Charles, 2020).

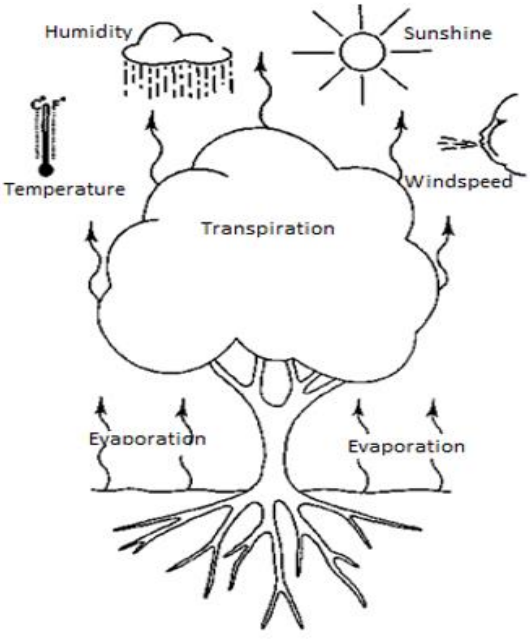


Figure 1.1 Major Factor Affecting Crop Water Requirement

1.4 Literature Review on Crop Water Requirement:

As both terms relate to the same volume of water, the relationship between crop water needs and crop evapotranspiration cannot be separated. Yet there are some things that set them apart. Crop water demand is the quantity of water that should be given while accounting for these losses, whereas crop evapotranspiration indicates real water losses (i.e., a hydrological term) (i.e., an irrigation management term). This amount of water represents the effective irrigation water supply required to achieve the greatest output. As a result, estimating crop evapotranspiration comes before estimating agricultural water requirements, while the latter typically represents crop evapotranspiration numbers aggregated over time (Gabr, 2022; Govere et al., 2020).

In order to properly apply irrigation water to the root zone and get effective precipitation, crop water requirements must be satisfied. The concept of agricultural water requirements became crucial with the introduction of large engineering projects that necessitated determining the water amounts to be delivered to newly irrigated regions. Agricultural water needs for real-time management reasons, where climatic data from the current season are utilised, are distinguished from crop water requirements for long-term planning purposes, which can use average climate or a climate with a specific likelihood of occurrence to estimate ETc. (Ali & Ali, 2010; Masia et al., 2021).

The effective use of water both in irrigated and rainfed areas for crop production is essential. The adoption of the exact or correct amount of water and correct timing of application is very essential for scheduling irrigations to meet the crop’s water demands and for optimum crop production. The irrigation scheduling based on crop water requirement (ETc) determined by multiplying crop coefficient (Kc) values with reference evapotranspiration (ETo), is one of the widely used methods. Based on the availability of weather data, various methods have been suggested (Gul et al., 2021; Yassen et al., 2020). Among all the methods Penman-Monteith method has been reported to yield consistently more accurate reference evapotranspiration (ETo) estimates across a wide range of climate conditions. Since Kc values are found to be crop, location and season specific, hence, need to be corrected for each location to determine ETc (Gupta et al., 2021; Mujtaba et al., 2022).

Increasing population is mostly to blame for the daily rise in water consumption in the residential, commercial, and agricultural sectors. The surface irrigation system in Pakistan is among the biggest in the world. Waterlogging is brought on by seepage into watercourses and canals, excessive irrigation, and irrigation water waste (Kia, 2013; Mujtaba et al., 2022). As a result of inadequate water resource management, waterlogging has grown to be a significant problem in the Lower Indus Basin. In the province of Sindh, 3.35 Mha (54.5% of the gross command area of 5.74 Mha) and 1.35 Mha (23.6%) of the 5.74 Mha have water tables between 1.5 and 3 metres, respectively. Nevertheless, seepage of water from irrigation canals and watercourses to underlying aquifers is not necessarily a true loss, because the water may be retrieved by pumping or utilised directly by plants, and so is a benefit for the population of the Indus plain. This water is a flexible resource that may be used whenever and in whatever amount, and it is relatively fresh compared to deep water. The tube well's installation and running expenses are reduced by the water's easy extraction and the pumping lift's modest size. To use shallow groundwater efficiently, it is crucial to comprehend the crop water needs (Mujtaba et al., 2022; Nadeem et al., 2020).

According to studies, Pakistani farming communities are experiencing and perceiving a number of climate-related threats, such as rising temperatures, irregular rainfall, insect infestations, and restricted water supplies (Hussain et al., 2023; Khan et al., 2019). Crop production reduction and water scarcity are two of the worst consequences of climatic variability observed by rural communities in Pakistan (Lu et al., 2019).

There is other research on climate risk management, adaptations, and adaption factors. Many studies investigate farmer knowledge of the presence of climate change and its potential consequences on crop growing. Based on simulation and crop modeling, a considerable number of agronomic field studies reveal detrimental impacts of climatic variability on a range of crop yields (Vogel et al., 2019). Climatic variability has also been linked to decreased yields and efficiency of rice-wheat farming systems in Pakistan's various agro-ecological zones. The 4.4% decrease in wheat output seen in 2018 compared to 2017 was mostly due to a lack of water. That indicates that rainfed wheat growing is at grave risk due to its reliance on rainfall for water requirements susutaibility (Mahmood et al., 2019; Nadeem et al., 2020).

Smith designed CROPWAT, a computer programming for FAO in 1991, which is used in water management across the world for calculating crop water requirements and irrigation scheduling with varied cropping patterns for irrigation planning.CROPWAT is an irrigation planning and management decision support system created by FAO's Land and Water Development Division.CROPWAT is intended to be a useful tool for doing conventional calculations for reference evapotranspiration, crop water requirements, and crop irrigation requirements, as well as for the design and operation of irrigation systems (Gul et al., 2021).

This programming allows for the generation of suggestions for enhanced irrigation performance, the scheduling of irrigation schedules under various water supply conditions, and the value of production under rain fed or deficit irrigation conditions.The amount of water required for the same crop varies depending on the weather.To achieve realistic water resource planning, comprehensive information on crop water requirements, irrigation extraction as a function of crop, soil type, and meteorological conditions is necessary.CROPWAT is an FAO irrigation supervision model that uses data from climate, crop, and soil to calculate reference evapotranspiration (ETo), crop evapotranspiration (ETc), and irrigation water demands (Gul et al., 2021).

Table 1.2 Literature Review on Crop Water Requirement

Sr	Study	Region	Period	Summary
1	**(Khan et al., 2019)**	Pakistan	(2005-2017)	The study uses CROPWAT 8.0 model to estimate Crop Water Requirement for wheat, sorghum, and millet in Peshawar district. It emphasizes the need for irrigation due to insufficient effective rainfall. Implementing appropriate irrigation practices is crucial for optimal crop growth and yield in the region.

2	**(Amin et al., 2022)**	Bangladesh	(1981–2010)	The study estimated irrigation requirements for rice crops in southeastern Bangladesh using the CROPWAT 8.0 model. Boro rice required the highest irrigation due to limited rainfall, while T. Aus and T. Aman rice showed varying irrigation needs. Farmers often exceeded model estimates, emphasizing the need for improved water management knowledge.
3	**(Gabr, 2022)**	Egypt	(1985-2018)	The study utilized the FAO-CROPWAT 8.0 model to estimate water requirements for major crops in Egypt. Five agroecological zones were identified based on reference evapotranspiration values. The findings emphasize the importance of efficient water resource management and suggest using the results for optimal irrigation planning and crop selection in Egypt.
4	**(Gul et al., 2021)**	Pakistan	(1980-2016)	This paper addresses the need for optimal irrigation scheduling in Pakistan’s northern dry mountain ecological zone to enhance maize crop yield under water scarcity. Using 36 years of climatic data, the study estimates crop water requirements and irrigation needs, showcasing the effectiveness of the irrigation management model. The findings offer recommendations for improved irrigation practices and scheduling to mitigate yield reduction in varying water supply conditions.

5	**(Moseki et al., 2019)**	Botswana	(2014-2016)	This study in Botswana focused on Jatropha cultivation and its water requirements. Using the CROPWAT model, it found an annual reference evapotranspiration (ETo) of 1456 mm and estimated Jatropha evapotranspiration (ETc) of 955.4 mm per growing season. The study emphasized the need for supplementary irrigation due to limited and variable rainfall in the region, and highlighted the importance of strategic irrigation scheduling to maximize Jatropha yield for biodiesel production.
6	**(Kia, 2013)**	Iraq	(2004-2012)	In this study conducted in Iraqi Kurdistan, the FAO Penman-Monteith equation and CROPWAT 8.0 program were employed to estimate evapotranspiration and effective rainfall for different crops. Two agro-climatic zones, Sangasar and Karkuk, were considered, and various crops including alfalfa, barley, beans, cabbage, grapes, maize, potatoes, sunflower, melons, tomatoes, and wheat were analyzed. The results revealed distinct water requirements for each crop and zone, providing valuable insights for efficient water management and irrigation planning in the region.

1.4.1 Impacts of Climate Change on Crop Water Requirement:

Water is a critical factor in agricultural productivity and the most valuable input. Irrigation water has helped farmers to raise agricultural yields by minimizing their reliance on rainfall patterns, therefore increasing average crop output while lowering interannual variability, since the beginning of plant cultivation over 10,000 years ago (Fischer et al., 2007). Irrigated land now accounts for more than 270 million hectares (Mha), or around 18% of total cultivated land. Agriculture is the greatest water consumer among human activities, accounting for 70% of overall anthropogenic use of renewable water resources – around 2630Gm3 /year (Gm3 /year) out of 3815Gm3 /year(Casolani et al., 2020). The majority of agricultural water withdrawals (AWWs) are lost in irrigation infrastructure (e.g., leaking and/or evaporating from irrigation canals and pipelines). Irrigated crops account for over 40% of total agricultural output, with yields that are generally twice as high as those of rain-fed crops. (Ashfaq et al., 2011; Lu et al., 2019)

For example, the Food and Agriculture Organization (FAO) estimates that irrigated cereals produce roughly 60% of a total of 1.2Gt in developing countries each year; thus, globally averaged irrigated cereal yields for developing countries are 3.9tons/ha, compared to roughly 1.8tons/ha under rain-fed conditions (Fischer et al., 2005). Aside from the direct effects of climate change on crop production, there is concern about future agricultural water requirements in relation to water availability as a result of the combined effects of climate change, rising population demands, and competition from other economic sectors as a result of future socioeconomic development (Bhadouria et al., 2019). Renewable water resources are increasingly being recognised as critical to the long-term viability of human society, even as a growing number of people live in water-stressed situations.(Arora, 2019; Raza et al., 2019).

Climate change is a frightening issue for agricultural production, especially in underdeveloped nations such as Pakistan. Increasing temperatures, shifting humidity, and shifting precipitation levels reduce agricultural productivity and farm revenue in developing countries (Masia et al., 2021). According to the latest estimates, 700 billion USD is needed to “curb climate change and enable developing nations to weather its worst repercussions,” according to a 2018 United Nations (UN) study. Climate variability has a significant impact on crop growth and production in agriculture. Temperature and precipitation, two of the most critical elements impacting rainfed crop cultivation, are directly affected by climate change (White et al., 2011). The significance of rainfed farming is obvious: Rainfed farming covers 80% of the world’s agricultural area, generating over 70% of global basic foods, including a significant amount from emerging countries.(Ahmad et al., 2014; Gao et al., 2019).

Pakistan is an agricultural country with arid and semi-arid climates, with rainfed farming accounting for 25% of total cultivated land. This research focuses on Pakistan’s rainfed cropping zone, where crop growing is strongly reliant on temperature and variable rainfall. Although considerable research has been conducted on climatic variability and crop farming in Pakistan (Haque & Khan, 2022). The implications of climatic variability on rainfed farming have yet to be investigated. As a result, this study seeks to quantify the effects of changing climate on wheat farming systems in Pakistan’s rainfed zone, where wheat is a key crop (Azmat et al., 2021). Although climate change impacts all crops, food crops are on the front lines since food insecurity is a serious concern in developing nations such as Pakistan (Gupta et al., 2021). Rising temperatures and greater rainfall variability are expected to hasten changes in the distribution and productivity of essential food crops in the next decades (Arshad et al., 2017; Malhi et al., 2021).

1.5 The Perspective of Pakistan:

Water scarcity in the country necessitates the development of new irrigation technologies and procedures that can properly utilize this valuable input. Furthermore, irrigation water management strategies must be implemented to attain high water use efficiency. Wheat is Pakistan’s main grain crop, is subjected to water stress/drought due to a lack of water and seasonal canal closures in December and January. Wheat is often watered four to five times in Punjab. At the crown root initiation (CRI) stage, the first irrigation is given 15-20 days following seeding. The following irrigation is scheduled at 30–35-day intervals. This water scarcity necessitates irrigation rescheduling, which should not have a substantial impact on grain yield but may limit the amount of water applied to the crop (Farooq & Gheewala, 2020)

Wheat’s water requirements range from 180 to 420 mm. As a result, there is enough room for research to determine the minimum amount of water should be applied to achieve the highest yield per millimeter of water applied. A study of soil moisture contents and patterns of moisture loss as the crop matures could aid in determining an appropriate irrigation plan for this goal.

Climate change is now widely acknowledged as a serious threat to humanity. Among the other driving forces are anthropogenic activities. The resulting effects on many sectors, particularly agriculture, are more pronounced. Because weather and temperature have no political bounds, developed industrial nations pollute their regional environment and ecosystem. As a result, developing and poor countries like Pakistan must suffer greatly (Haider & Ullah, 2020).

Aside from that, the availability and reservation of water resources will be a major concern in the future, both on an international and regional scale. Water supply would also be a major issue for the country soon due to political and strategic interactions with surrounding countries. Future climate forecasts show a rising tendency in surface temperatures, which will eventually augment several agrometeorological elements such as reference crop evapotranspiration (Javed et al., 2020).

A current study is being conducted to examine the implications of rising temperatures on ETo and agricultural water demand in the country. According to climate estimates from credible authorities such as the IPCC, increasing trends of 1-3°C are predicted in the next 50 years. It has been determined that the southern portion of Pakistan will be the least affected in the future. However, in the northern half, there will be a dramatic rise in water demand compared to now, increasing the danger of crop failure in rain-fed areas where extra irrigation is not available (Abbas, 2020).

However, in Pakistan, farmers frequently over-irrigate their crops because they are unaware of the water needs of their crops, and (ii) they think that using more water will increase their production. Contrarily, more water applications lead to reduced crop output as they deplete nutrients from the root zone and have a negative impact on water productivity. In skimming water applications (freshwater covering saline water), more water applications, greater costs, a larger danger of salt accumulation in the root zone, and reduced net revenue are all frequent outcomes. A major barrier to maximising irrigation water use is farmers' ignorance of the optimum irrigation scheduling. Sugarcane, cotton, and wheat are the principal crops grown in the Lower Indus Basin (Alvar-Beltrán et al., 2021). Yet it is still unknown what amount of water their crops would need in high water-table situations. Agro-climatic factors, soil type, crop type, water-table conditions, and to a lesser extent cultural practices, impact the amount of water that crops need to grow (Javed et al., 2020; Purakayastha et al., 2019).

1.5.1 Cotton and Wheat in Pakistan:

The fourth-largest producer of cotton in the world is Pakistan. The cotton belt extends over 1200 kilometers of the Indus delta. The primary cash crop in Pakistan is cotton, which is grown in parts of Southern Punjab and Sindh. During the growing season, it needs high temperatures, and during the harvesting season, it needs low temperatures. For instance, heat waves have a considerable impact on its production and have led to serious economic issues (Abbas, 2020).

Cotton, the second-most significant crop and a key component of the economy of Pakistan, is an agricultural nation. 4.5% more agricultural value added is produced, contributing an additional 0.8% to the overall GDP. 11 946 million bales were produced overall in 2017–18, whereas 9 861 million bales were produced overall in 2018–19, a 17.5% reduction. Reduced farmer incentives caused a decrease in cotton production compared to the prior year, which led to a decrease in the cultivated area from 2 700 000 to 2 373 000 hectares (Arshad et al., 2021). The fourth-largest producer of cotton in the world is Pakistan. With the introduction of cotton biotechnology in Pakistan in 1992–1993 a variety of tactics have been researched to improve cotton quality and yield. Breeding programs, cloning, cotton changes, germplasm exploitation, molecular markers-based technologies, and expanded capacity building of different funding and research agencies have all been taken into consideration (RAZZAQ et al., 2021; Shabbir & Yaqoob, 2019).

Pakistan’s third-largest industry is the wheat industry. In terms of acreage (8.5 million hectares), Pakistan is the tenth-largest producer of wheat, while in terms of annual output, it is the 59th-largest (21.0 million tonnes). According to previous research, climatic factors have a greater influence on Pakistan’s wheat output than non-climatic ones. In Punjab, a similar favorable effect on wheat productivity was seen. Climate change is recognised as a big calamity for Pakistan’s economic status, adding to food insecurity in the country, according to the State Bank of Pakistan’s (SBP) annual report. According to predictions, wheat production would decline by 1.5 to 2.6 percent by 2020. It has also been stated that climate change has shortened the wheat and rice seasons, perhaps resulting in a low harvest of food crops in Pakistan (Mahmood et al., 2020; Muzammil et al., 2020).

The rice-wheat cropping system is critical to Pakistan, accounting for around 62% of national calorie intake and spanning over 2.2 Mha. The Punjab of Pakistan is a key source of this output and is separated into three primary cropping zones: rice-wheat (RW), mix wheat (MW; wheat with sugarcane, maize, potato, or fodder crops, etc.), and cotton-wheat (CW) (Ye et al., 2015). This zone is based on the districts of Gujrat, Mandi Baha Uddin, Sialkot, Narowal, Gujranwala, Nankana Sahib, Sheikhupura, Lahore, and Hafizabad and encompasses 1.1 Mha in a subhumid climate. The rice-wheat cropping system is used on a wide range of soils and with a variety of agronomic and irrigation strategies(Kaushika et al., 2019). The Upper Chenab, Marala Ravi, and Central Bari Doab canals provide surface water for agriculture. Groundwater has been extensively exploited over time, first by the public sector in the 1960s and then by the private sector after the 1980s, resulting in enormous increases in cropping intensity from 60% to more than 150%. Groundwater is the most important contributor to crop production, accounting for almost two-thirds of the total inflow in the Punjab rice-wheat zone (Azmat et al., 2021; Khaliq et al., 2019).

Wheat is Pakistan’s most popular food grain crop and a significant source of calorific intake for the people in its different forms. Being the staple meal of millions of Pakistanis, it accounts for the lion’s share of the total farm area under cultivation as well as output, accounting for 9.1% of agricultural value added and 1.7% of Pakistan’s GDP. Pakistan is one of the countries most affected by climate change due to its poor infrastructure and weak adaptation ability. While contributing very little to global warming, the country’s sensitivity to climatic unpredictability is growing. Pakistan was placed 12th, 8th, and then 7th in the long-term Climate Risk Index (CRI) in 2012, 2015, and 2016, respectively. Because of its dry and diversified geographical character, as well as few natural resources, its farming industry is one of the most sensitive to climate change. In Pakistan, the agriculture industry accounts for 18.9% of the total GDP while employing 42.3% of the population.(Gul et al., 2019; Jia et al., 2021).

1.6 Justification of Study:

I. To date, none of the research on crop water requirements that have been examined has focused on future perspectives utilizing CMIP6 data over Pakistan.
II. To date, no study has used DCPP, a recently established climate prediction data set for a decades ahead utilizing a series of retrospective projections.
III. To date, no study has employed a robust climate prediction dataset that explores how naturally forced perturbations affect projections to determine future crop water requirements over Pakistan.

The use of a shorter-term decimal climate forecast product to close this gap in the currently available literature and inform stakeholders about the implications of climate change is thus justifiable, and this remains the core goal of this thesis.

1.7 Objectives of the Study:

The objectives of this research are:

- To estimate the frequency of crop water requirement for the Kharif (Cotton) and Rabi (Wheat) seasons over Pakistan.
- To study the impact of climate change on crop water requirement and its future projection (2022-2031)

Chapter 2

2 DATA AND METHODOLOGY

2.1 Study Area:

This study will be the focus on whole Pakistan region, and it will be divided based on 4 provinces of Pakistan: Punjab, Khyber Pakhtunkhwa (KPK) , Sindh, and Balochistan.

Table 2.1 Information about the study area

S no	Provinces	Longitude Extent	Latitude Extent
1	**Punjab**	69.32 to 75.38	27.70 to 33.97
2	**Sindh**	66.65 to 71.12	23.68 to 28.52
3	**Khyber Pakhtunkhwa**	69.23 to 74.13	31.07 to 36.91
4	**Balochistan**	60.87 to 70.24	24.88 to 32.07

Of the 30 million hectares of total cultivable land in Pakistan, 60% is irrigated. Around 89% of the total irrigated land is made up of Punjab and Sindh (Peña-Arancibia et al., 2021).

The usual climate of Punjab is subtropical, with summer temperatures exceeding 45 degrees Celsius and winter temperatures as low as 0 degrees Celsius. The province’s average annual rainfall is 400mm. Despite the agricultural industry in Punjab contributes significantly to Pakistan’s overall economy, it is under stress from serious climate change-induced consequences such as floods and droughts. Wheat and cotton are two key commodities cultivated in Punjab that contribute significantly to Pakistan’s economy. Cotton, often known as white gold, is a cash crop in Pakistan and accounts for the majority of export profits. Wheat is another important crop, accounting for 2.2% of Pakistan's GDP and around 10.3% of its agricultural economy (Ali et al., 2022).

Sindh’s climate is likewise subtropical, with an average annual rainfall of 200mm at the highest point, temperatures that exceed 46 degrees Celsius in the summer and drop to 2 degrees Celsius in the winter). The left and right banks of the Indus Basin help to define crop zones in Sindh. The left bank consists of a cotton-wheat zone and a sugarcane mix zone, whereas the right bank consists only of a rice-wheat zone. Sindh agriculture zones are characterised by shallow groundwater levels of up to three metres in depth. According to research, crops such as sugarcane, rice, wheat, and cotton absorb groundwater in fresh groundwater quality zones. Cotton-wheat zones extend from dry climatic districts to desert environments, whereas sugarcane mix zones are located in the province's center region, where canal water supply is perennially supplied by fresh groundwater zone due to its closeness to the Indus River (Farooq & Gheewala, 2020).

The city's annual temperature is 18.53^{o}C (65.35^{o}F), which is -2.36% lower than the national average. Khyber Pakhtunkhwa receives around 124.39 millimeters (4.9 inches) of precipitation per year and has 137.46 wet days (37.66% of the time). Wheat cultivation is more important in Khyber Pakhtunkhwa than in other provinces. The total wheat need in 1071.8 thousand tonnes was produced in 2007–2008, compared to 2686.0 thousand tonnes in Khyber Pakhtunkhwa (Gul et al., 2019). This is due to the fact that, in comparison to the country's average yield, wheat production in even irrigated regions in 2007–08 was fairly low (1968 kilograms per hectare and 2451 kilogrammes per hectare) (Ali & Khan, 2014).

Summers in Balochistan are hot and arid. Summers are exceedingly hot in the dry zones of the Chaghi and Kharan districts. In the summer, temperatures on the plains can reach 120 degrees Fahrenheit (50 degrees C). With the temperature, winters on the plains are moderate. Balochistan's yearly precipitation ranges from 2 to 20 inches (50 to 500 mm). Wheat is a major source of staple food in Balochistan. Wheat is grown under both irrigated and rainfed conditions, accounting for 8.5 and 15% of the total area in 1998-99, respectively. As a result, it was decided to examine the performance of the wheat crop in irrigated Balochistan, which provided 93% of the province's total output (Shah et al., 2002).

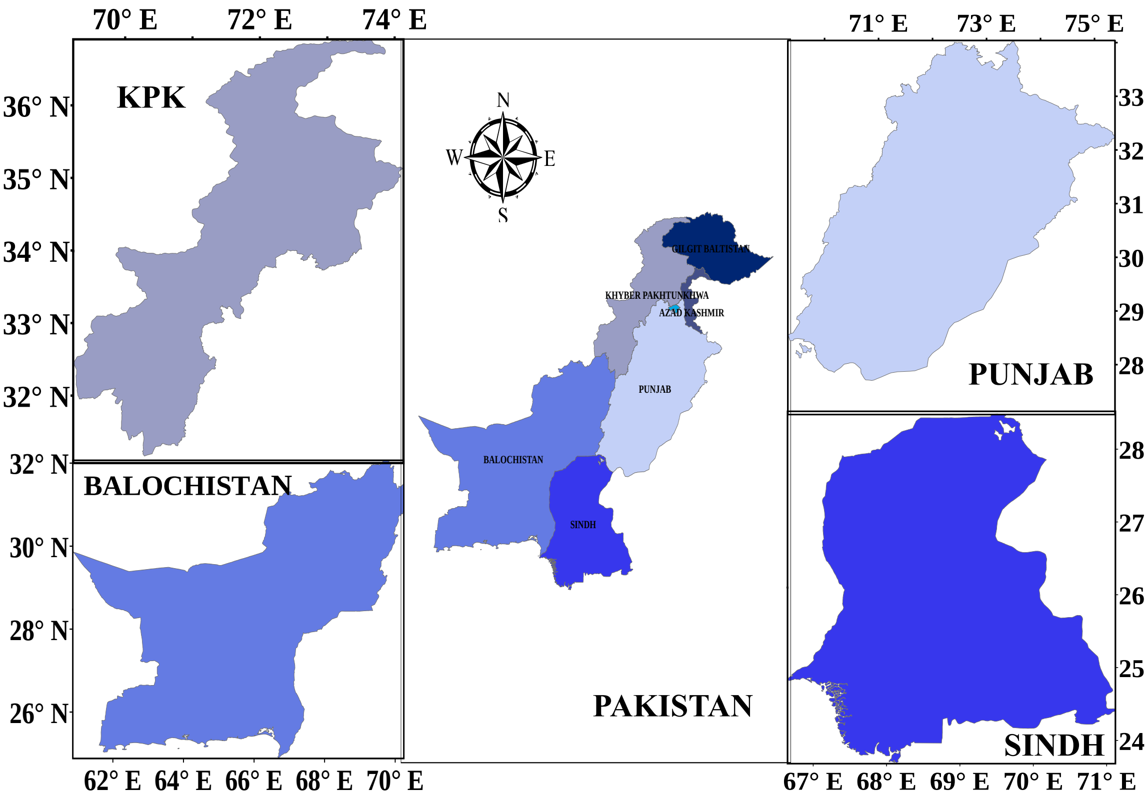


Figure 2.1 Map showing the study area.

2.2 Methodology:

The research methodology is given in Figure 2.2

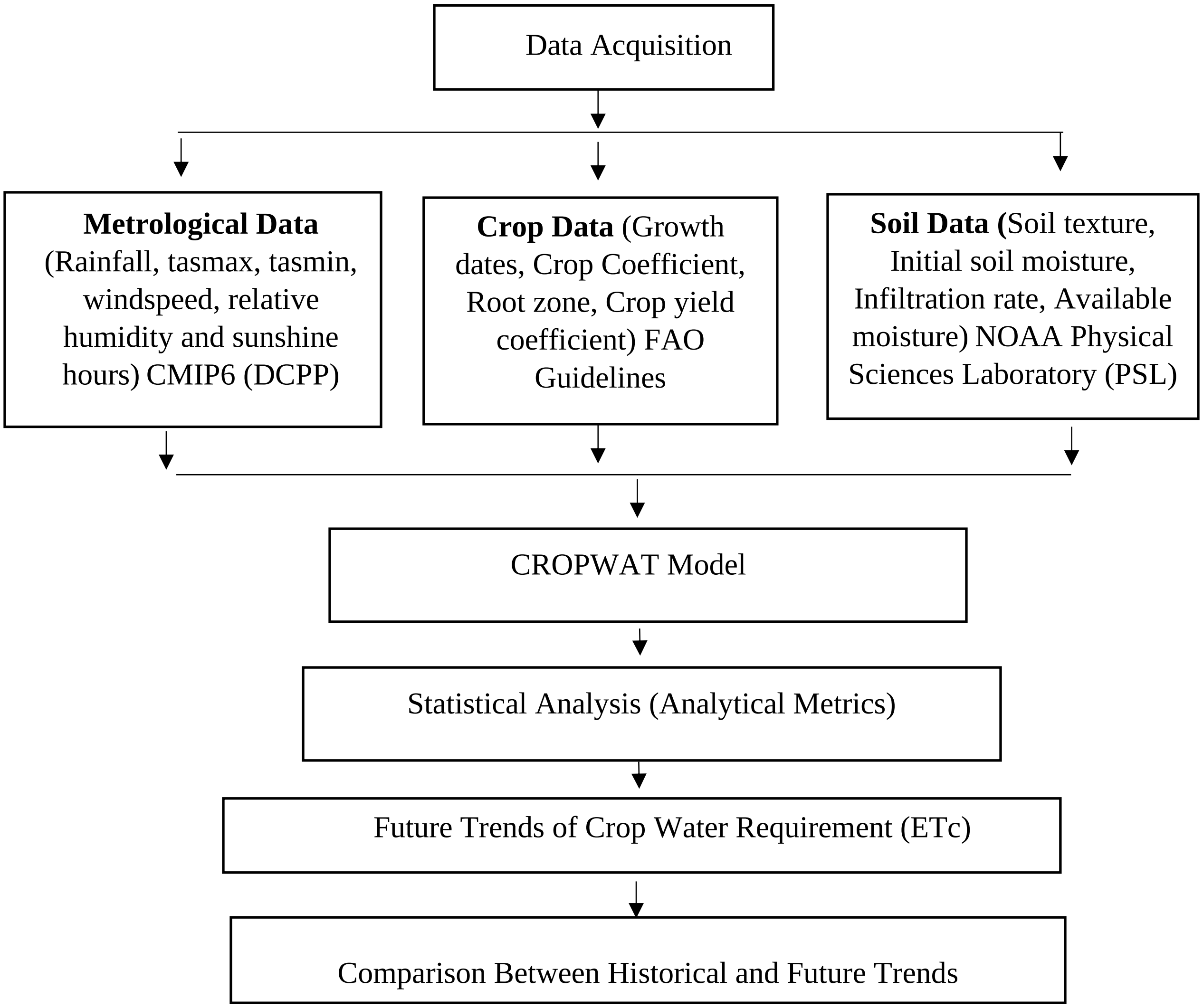


Figure 2.2 Research methodology flow chart

2.3 Metrological Data:

2.3.1 The Coupled Model Intercomparison Project (CMIP6):

The World Climate Research Programme (WCRP) Coupled Model Intercomparison Project, which began in 1995, is presently in its sixth phase (CMIP6). The Earth System Grid Federation (ESGF) powers CMIP6, which is hosted by the Department of Energy’s Lawrence Livermore National Laboratory.

CMIP6 coordinates model intercomparison activities and experiments that have chosen a common infrastructure for gathering, organizing, and disseminating output from models conducting common sets of experiments.

Different nodes are provided on the CMIP6 website using nodes and criteria input. It includes MIP Era, Source ID, Nominal Resolution, variables (parameters) count, and so on. That input determines the essential data for the historical era (2013 – 2021) and future projection (2022 – 2030), which can then be readily downloaded into your digital device. The variables being retrieved include minimum and maximum temperatures, relative humidity, wind speed, and precipitation as you can see in table 2.2.

Table 2.2 Information of variable retrieved from CMIP6 data repositories.

Variables	Output variable name	Units
Maximum Temperature	tasmax	^{o}C
Minimum Temperature	tasmin	^{o}C
Relative Humidity	hurs	%
Eastward Wind	uas	km/day
Northward Wind	vas	km/day
Precipitation Flux	pr	MJ/m^{-2} /s^{-1}

2.3.1.1 The Decadal Climate Prediction Project (DCPP):

The phrase “decadal prediction” relates to projections made on yearly, multi-annual, and decadal timescales. Predictability studies and retrospective predictions (also known as hindcasts) utilising climate models and statistical approaches are used to investigate the potential and ability to develop skillful forecasts over a variety of periods.

The temperature has traditionally been the focus of predictability and prediction research, and there is evidence of competence in the prediction of changes in annual mean temperature throughout most of the world for several years, subject to forecast initialization. When the prediction range extends, the initialization skill decreases, but some skill is kept owing to external forcing from greenhouse gases, aerosols, and volcanoes.

Precipitation and other factors are now more difficult to predict than temperature, although progress is expected as a result of the Decadal Climate Prediction Project (DCPP) and other research and investigations.

Under the supervision of the Working Group on Sub-seasonal to Interdecadal Prediction (WGSIP), the DCPP Panel manages the scientific and practical elements of decadal climate prediction research within WCRP. The DCPP is split into three sections.:

- **Hindcasts, Component A**: The design and execution of a coordinated decadal prediction (hindcast) initiative in collaboration with the seasonal prediction and climate modeling communities, as well as the creation of a large data repository for study and applications.
- **Forecasts (Component B)**: The continuation of experimental quasi-operational decadal climate forecasts in order to allow multi-model yearly to decadal forecasting, as well as their application to societal demands.
- **Component C, Predictability, Mechanisms, and Case Studies**: planning and organising decadal climate forecast studies, as well as case studies of unusual climatic changes and fluctuations, including research into the systems behind this behavior.

The Decadal Climate Prediction Project (DCPP) employs a series of retrospective forecasts to evaluate our capacity to anticipate climate variations from a year to a decades ahead. Predictions for future customers are also created in near-real time. Additionally, the DCPP examines how disturbances such as volcanoes impact projections and, more broadly, what new information can be gained about the mechanisms that regulate climate change via case studies of prior climate behavior.

2.4 CROPWAT 8.0:

CROPWAT 8.0 for Windows is a computer application that determines agricultural water and irrigation requirements based on current or new meteorological and crop data. Furthermore, the application allows for the construction of irrigation schedules for a variety of management settings, as well as the calculation of scheme water supply for a variety of crop patterns.

CROPWAT 8.0 for Windows contains a slew of new and updated features.

These are some examples:

- Monthly, deacdes and daily climatic data are used to calculate ETo.
- Backward compatibility for using CLIMWAT database data.
- The capacity to estimate climate data when observed values are unavailable.
- A ten-year and daily estimate of agricultural water requirements using novel calculation techniques that include crop-coefficient modifications.
- Computation of agricultural water requirements and irrigation scheduling for dry crops, paddy rice, and upland rice.
- User-adjustable watering regimens that are interactive.
- Tables of daily soil water balance outputs
- Simple storage and retrieval of sessions and user-defined irrigation programmes
- Graphical displays of input data, crop water requirements, and irrigation schedules.

The CROPWAT 8.0 calculation methods are based on FAO recommendations as specified in FAO Irrigation and Drainage Series article No. 56, “Crop Evapotranspiration – Guidelines for Calculating Crop Water Needs.” The major function of CROPWAT is to compute crop water requirements and irrigation schedules depending on user input. These values can be input manually or imported from other programs into CROPWAT.

For the purpose of calculating crop water requirements (ETc), CROPWAT needs evapotranspiration data (ETo). With the use of the Penman-Monteith formulae, CROPWAT uses the user’s measured ETo values or data on temperature, humidity, wind speed, and sunlight to produce an ETo estimate.

Moreover, rainfall data is necessary, and CROPWAT uses it to provide effective rainfall data that is used as an input in crop water requirement and scheduling calculations. The last need for crop water requirement computations is crop data (dry crop or rice), soil data, and irrigation schedules if the user wishes to compute these (dry crop or rice).

CROPWAT typically determines ETc and schedules for a single crop, but it may also determine a scheme supply, which is the total number of crops’ crop water requirements with their individual planting dates (a so-called cropping pattern). Both for calculating and entering data.

2.4.1 Program Structure:

The CROPWAT program consists of eight modules, three of which are for computations and five of which are for data entering. These modules are easier to reach than the CROPWAT main menu because of the Modules bar, which is permanently located on the left side of the main window. As a result, the user may easily include various meteorological, agricultural, and soil data to calculate the quantity of water that crops will need, as well as irrigation timings and supply plans.

CROPWAT’s data entry modules are as follows:

- **Climate/ETo**: for entering climatic data or measured ETo data to enable Penman-Monteith ETo computation.
- **Rain**: putting rainfall data in and figuring out effective rainfall.
- **Crop (dry crop or rice):** entry of crop information and planting date.
- **Soil**: for entering soil data (Just necessary for scheduling irrigation).
- **Crop pattern**: for incorporating a cropping pattern into the system supply estimations.

It should be noted that the Climate/ETo and Rain modules not only accept data but also calculate it, particularly Radiation/ETo and Effective rainfall.

CROPWAT’s calculation modules are as follows:

- **CWR/ETc** – for calculating crop water requirements.
- **Schedules (dry crop or rice)** – for irrigation schedule calculation
- **Scheme** – for scheme supply calculation based on a specified cropping pattern.

2.5 CROPWAT Modules:

The Modules bar can be found on the left side of the main CROPWAT window. The buttons on the Modules bar allow immediate access to the CROPWAT Programme available modules.

When you first click on the Climate/ETo, Rain, Crop, Soil, or Cropping Pattern buttons, a data-entering window for the corresponding module will appear. You can begin manually inputting data, open an existing data file using the File>Open menu option (or more simply by selecting the Open button on the Toolbar), or paste a table from the clipboard that was copied from, say, an Excel spreadsheet. The Climate/ETo, Rain, and Crop data windows will open with the default data type for that data (monthly ETo Penman-Monteith in the case of the Climate/ETo module). By using the drop-down menu from the new button on the Toolbar, you can rapidly switch to another data type for that module (for example, monthly measured ETo in the case of Climate/ETo) as shown in figure 2.3 . Each input data module of Cropwat 8.0 is discuss in the appendices A .

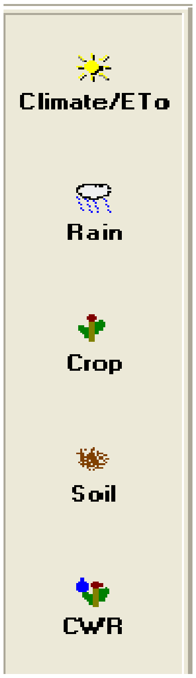
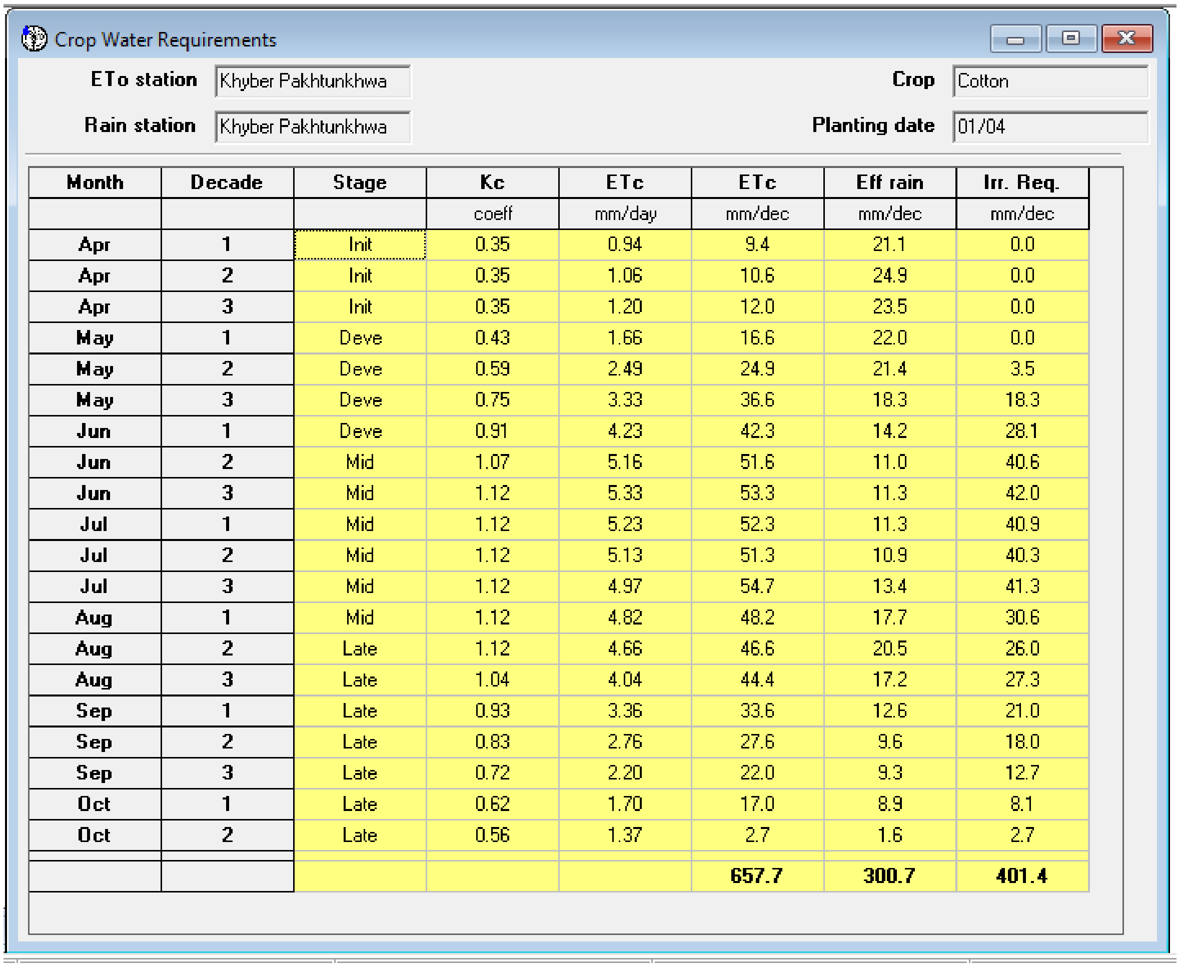


Figure 2.3 CROPWAT modules

2.5.1 Crop Water Requirement (ETc) Module:

The crop water need module comprises computations that provide the crop's irrigation water requirement throughout the whole growing season as the difference between Crop evapotranspiration under standard circumstances (ETc) and Effective rainfall as shown in figure 2.4.



ETo station: Khyber Pakhtunkhwa
Crop: Cotton
Rain station: Khyber Pakhtunkhwa
Planting date: 01/04

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Apr	1	Init	0.35	0.94	9.4	21.1	0.0
Apr	2	Init	0.35	1.06	10.6	24.9	0.0
Apr	3	Init	0.35	1.20	12.0	23.5	0.0
May	1	Deve	0.43	1.66	16.6	22.0	0.0
May	2	Deve	0.59	2.49	24.9	21.4	3.5
May	3	Deve	0.75	3.33	36.6	18.3	18.3
Jun	1	Deve	0.91	4.23	42.3	14.2	28.1
Jun	2	Mid	1.07	5.16	51.6	11.0	40.6
Jun	3	Mid	1.12	5.33	53.3	11.3	42.0
Jul	1	Mid	1.12	5.23	52.3	11.3	40.9
Jul	2	Mid	1.12	5.13	51.3	10.9	40.3
Jul	3	Mid	1.12	4.97	54.7	13.4	41.3
Aug	1	Mid	1.12	4.82	48.2	17.7	30.6
Aug	2	Late	1.12	4.66	46.6	20.5	26.0
Aug	3	Late	1.04	4.04	44.4	17.2	27.3
Sep	1	Late	0.93	3.36	33.6	12.6	21.0
Sep	2	Late	0.83	2.76	27.6	9.6	18.0
Sep	3	Late	0.72	2.20	22.0	9.3	12.7
Oct	1	Late	0.62	1.70	17.0	8.9	8.1
Oct	2	Late	0.56	1.37	2.7	1.6	2.7
					657.7	300.7	401.4

Figure 2.4 Crop water requirement (ETc) module.

2.5.1.1 Crop Coefficient Approach:

Crop evapotranspiration may be computed using meteorological data and the FAO Penman-Monteith technique by directly combining crop resistance, albedo, and air resistance variables. Because there is still a significant dearth of knowledge for many crops, the Penman-Monteith technique is used to estimate the standard Reference crop's evapotranspiration rate, i.e., Reference evapotranspiration (ETo). Crop coefficients (Kc) are experimentally measured ratios of ETc/ETo that are used to connect Crop evapotranspiration under standard circumstances (ETc) to ETo. This is referred to as the crop coefficient strategy.

$$ETc = Kc \times ETo$$

The ETo estimation takes into account radiation, air temperature, humidity, and wind speed. As a result, ETo is a measure of climatic demand, whereas Kc changes mostly with crop attributes and only to a lesser amount with temperature and soil evaporation. This allows for the transfer of conventional Kc values between places and climates. This has been a major cause for the crop coefficient method and the Kc factors created in previous research’s widespread popularity and utility.

The FAO Penman-Monteith equation is used to define and compute ETo. Kc is an aggregation of the impacts of four major features that differentiate the crop under consideration from the Reference crop. These characteristics are:

- **Crop height:** The crop height affects the FAO Penman-Monteith equation’s aerodynamic resistance component (ra) and the turbulent transport of vapor from the crop into the atmosphere. In the entire version of the FAO Penman-Monteith equation, the (ra) term appears twice.
- **Crop-soil surface albedo (reflectance):** The albedo is affected by the proportion of land covered by plants and by the soil surface dampness. The albedo of the crop-soil surface affects net radiation absorption, which is the principal source of energy exchange in the evaporation process.
- **Leaf area (number of stomata):** leaf age and condition, and the degree of stomatal regulation all influence crop resistance to vapor transport. The surface resistance is influenced by the canopy resistance (rs).
- Soil evaporation, particularly from exposed soil.

The surface resistance is influenced by the moisture of the soil surface and the proportion of the ground covered by plants (rs). The vapor transfer rate from the soil is significant after soil precipitation, especially for crops with insufficient ground cover. The (bulk) surface resistance, rs, is determined by the combined surface resistance of the canopy and the soil. In the FAO Penman-Monteith equation, the surface resistance element describes the resistance to vapor passage from within plant leaves and under the soil surface.

The Kc in the given equation allows for ETc prediction. This depicts the top envelope of crop evapotranspiration and situations in which crop growth or evapotranspiration is not limited by water scarcity, crop density, disease, weed, insect, or salinity stresses. If necessary, the ETc predicted by Kc is adjusted to non-standard circumstances using the Crop evapotranspiration/ crop water need under non-standard settings (ETc adj) if any environmental variable or trait is known to have an influence on or restrict crop water demand (ETc).

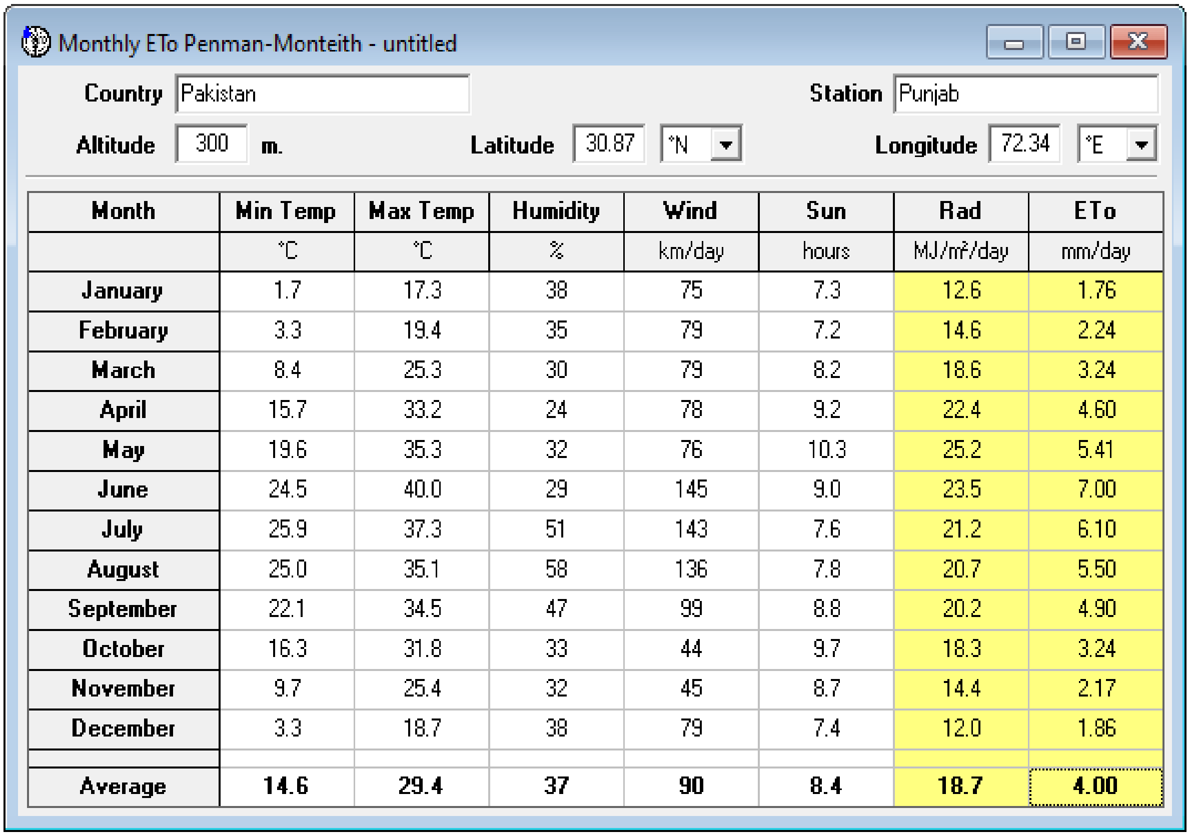
2.6 Input Data for CROPWAT 8.0:

Climate, soil, and crop data, as well as irrigation and rain data, are used in water and irrigation measures. Rainfall (day/decads/monthly) and reference evapotranspiration (Dm/monthly) are the climatic input data required. The FAO Penman-Monteith approach calculates reference evapotranspiration (ETo) based on maximum and minimum temperature, wind speed, humidity and sunlight hours.

2.6.1 Climate Data:

Meteorological data for the Pakistan 4 provinces includes minimum and maximum temperatures, wind speed (kilometers per day), air humidity (percentage), and sunlight duration (hours), as well as latitude, longitude, and elevation value. Climate/ETo has made use of CMIP6 data for the historical period (2013-2021) and future predictions (2022-2030).

The obtained ETo values are based on the Penman-Monteith technique, and an example of Punjab hindcast data is presented in Figure 2.5.



Monthly ETo Penman-Monteith - untitled

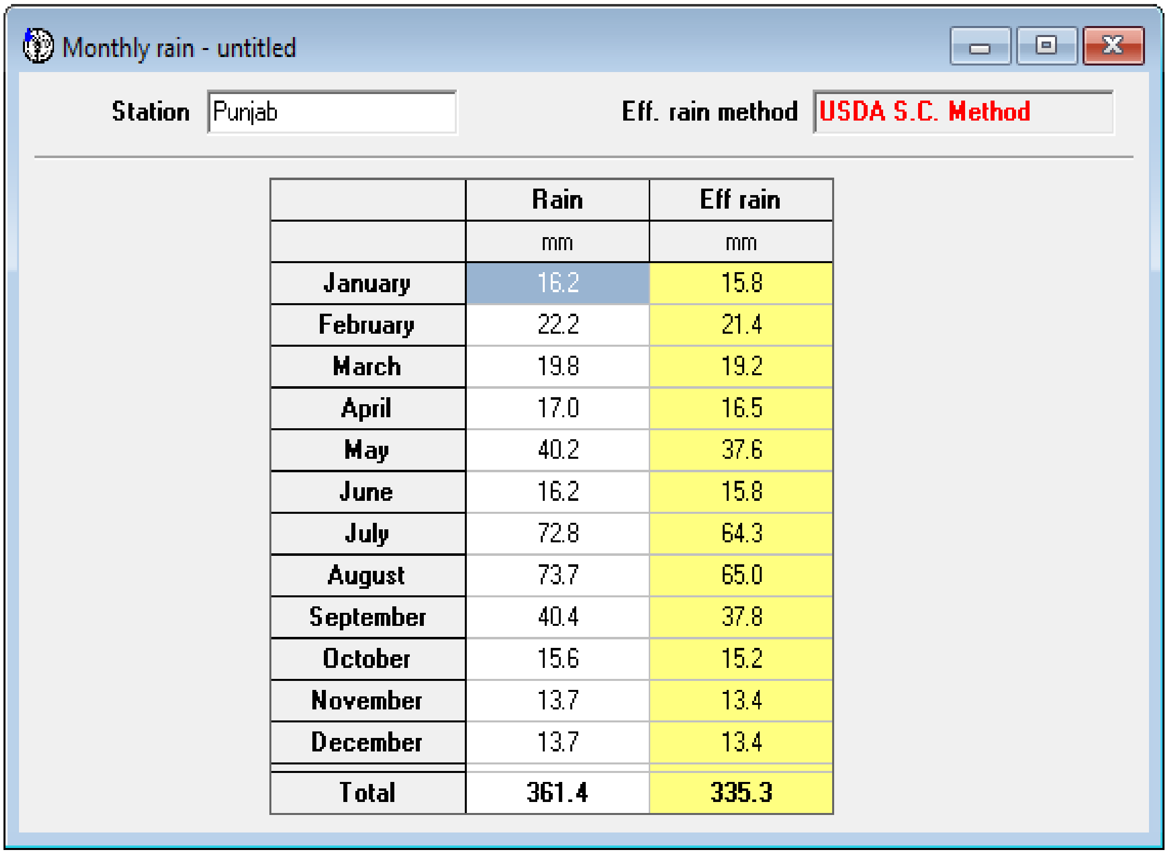
Country: Pakistan
Station: Punjab
Altitude: 300 m.
Latitude: 30.87 °N
Longitude: 72.34 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m^2/day	mm/day
January	1.7	17.3	38	75	7.3	12.6	1.76
February	3.3	19.4	35	79	7.2	14.6	2.24
March	8.4	25.3	30	79	8.2	18.6	3.24
April	15.7	33.2	24	78	9.2	22.4	4.60
May	19.6	35.3	32	76	10.3	25.2	5.41
June	24.5	40.0	29	145	9.0	23.5	7.00
July	25.9	37.3	51	143	7.6	21.2	6.10
August	25.0	35.1	58	136	7.8	20.7	5.50
September	22.1	34.5	47	99	8.8	20.2	4.90
October	16.3	31.8	33	44	9.7	18.3	3.24
November	9.7	25.4	32	45	8.7	14.4	2.17
December	3.3	18.7	38	79	7.4	12.0	1.86
Average	14.6	29.4	37	90	8.4	18.7	4.00

Figure 2.5 Input data of climate module for CROPWAT 8.0

2.6.2 Rainfall Data:

Rainfall data is one of the factors used to determine the relevance of agricultural water needs. For rainfall, CMIP6 data from the historical period (2013-2021) and future predictions (2022- 2030) were utilised. Figure 2.6 is an example of Rainfall data input for Punjab hindcast data.



Station: Punjab

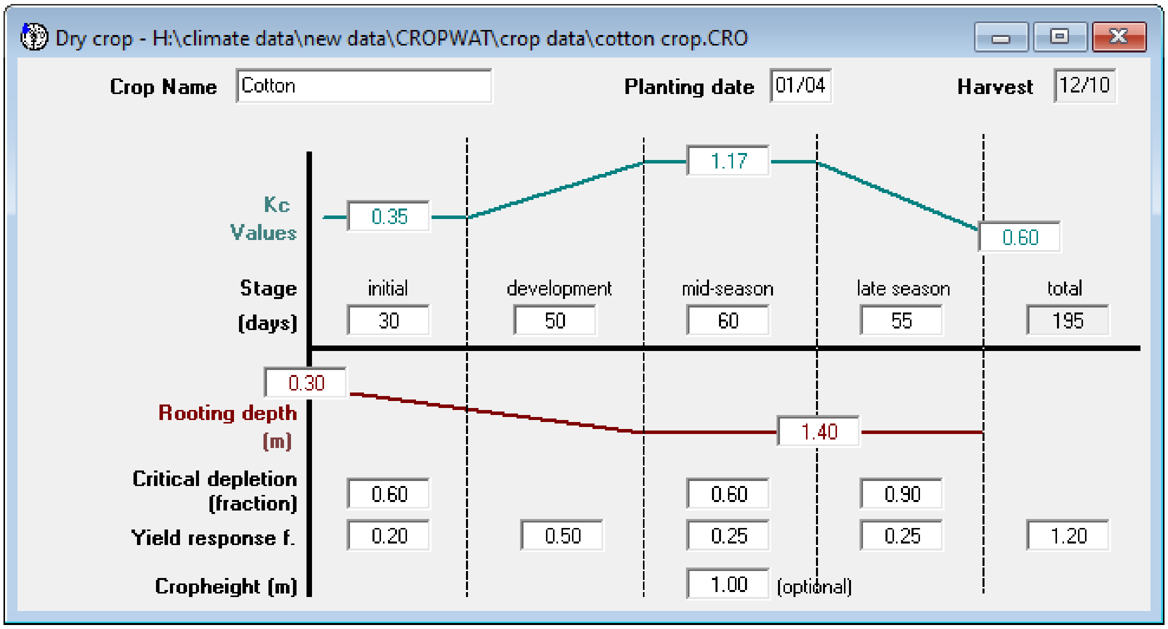
Eff. rain method: USDA S.C. Method

	Rain	Eff rain
	mm	mm
January	16.2	15.8
February	22.2	21.4
March	19.8	19.2
April	17.0	16.5
May	40.2	37.6
June	16.2	15.8
July	72.8	64.3
August	73.7	65.0
September	40.4	37.8
October	15.6	15.2
November	13.7	13.4
December	13.7	13.4
Total	361.4	335.3

Figure 2.6 Input data of rainfall module for CROPWAT 8.0

2.6.3 Crop Data:

The input crop characteristics data include the total days at each stage of growth, the Kc value for each stage of growth, critical depletion, root depth, and crop yield response parameters. The yield response factor (Ky), which comprises temperature, soil, and crop factors that reduce crop yields from evapotranspiration in comparison to their potential yield, is the percentage of the decrease of comparative yield to the deficits in comparative evapotranspiration. Data about crops is acquired from FAO Guidelines. Examples of crop data entered for the cotton and wheat seasons are shown in Figures 2.7 and 2.8, respectively.

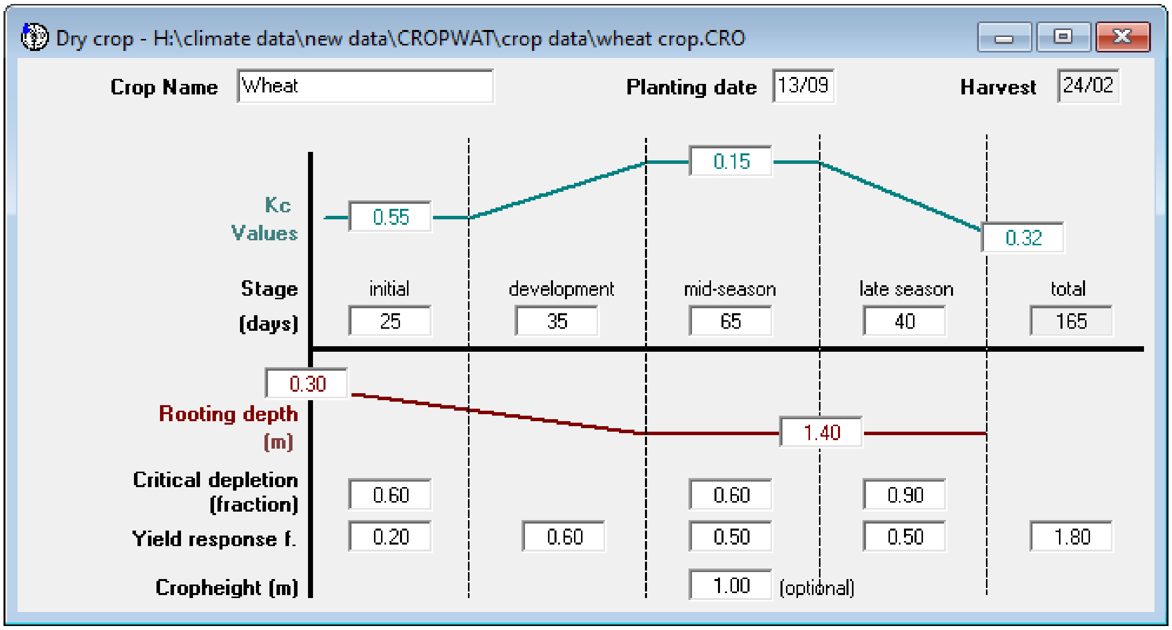


Dry crop - H:\climate data\new data\CROPWAT\crop data\cotton crop.CRO

Crop Name: Cotton
Planting date: 01/04
Harvest: 12/10

	initial	development	mid-season	late season	total
Kc Values	0.35		1.17		0.60
Stage (days)	30	50	60	55	195
Rooting depth (m)	0.30			1.40	
Critical depletion (fraction)	0.60		0.60	0.90	
Yield response f.	0.20	0.50	0.25	0.25	1.20
Cropheight (m)			1.00	(optional)	

Figure 2.7 Input data of cotton season in crop module for CROPWAT 8.0



Dry crop - H:\climate data\new data\CROPWAT\crop data\wheat crop.CRO

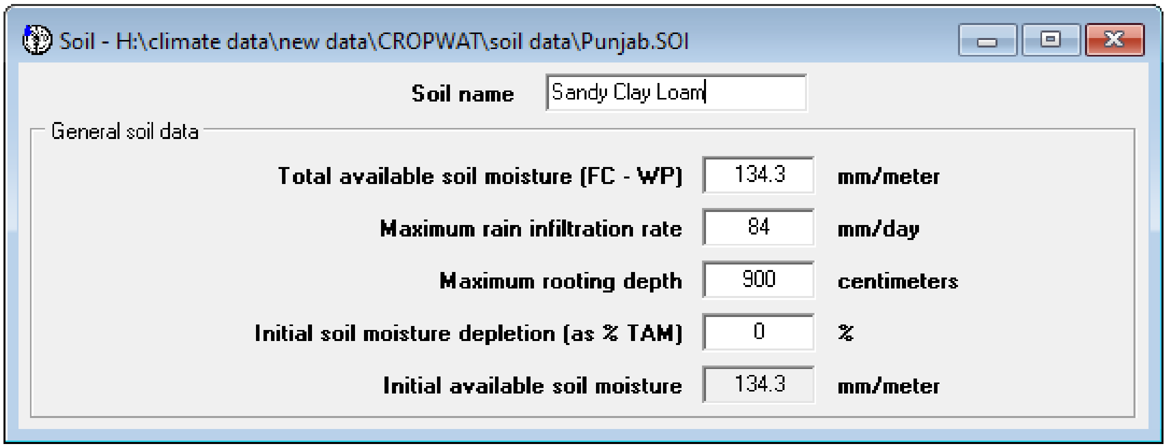
Crop Name: Wheat
Planting date: 13/09
Harvest: 24/02

	initial	development	mid-season	late season	total
Kc Values	0.55		0.15		0.32
Stage (days)	25	35	65	40	165
Rooting depth (m)	0.30			1.40	
Critical depletion (fraction)	0.60		0.60	0.90	
Yield response f.	0.20	0.60	0.50	0.50	1.80
Cropheight (m)			1.00	(optional)	

Figure 2.8 Input data of wheat season in crop module for CROPWAT 8.0

2.6.4 Soil Data:

The CROPWAT program requires fundamental soil data such as total soil moisture available, maximum rainfall infiltration rate, maximum root depth, first depletion of soil moisture content, and initially soil moisture available. Data about crops is acquired from NOAA Physical Sciences Laboratory (PSL) Data sets. Figure 2.9 is an example of soil data entry for Punjab, which is sandy clay loam soil. The remaining provinces' data is shown in Table 2.3.



Soil - H:\climate data\new data\CROPWAT\soil data\Punjab.SOI

Soil name: Sandy Clay Loam

General soil data

Total available soil moisture (FC - WP): 134.3 mm/meter

Maximum rain infiltration rate: 84 mm/day

Maximum rooting depth: 900 centimeters

Initial soil moisture depletion (as % TAM): 0 %

Initial available soil moisture: 134.3 mm/meter

Figure 2.9 Input data of soil module for CROPWAT 8.0

Table 2.3 Input data of soil parameters for CROPWAT 8.0

Provinces	Soil Type	Total Available Water (TAW)	Maximum infiltration rate	Maximum rooting depth	Initial soil moisture depletion
Punjab	Sandy Clay Loam	134.3	84	900	134.3
Sindh	Medium(loam)	55	40	900	55
Khyber Pakhtunkhwa	Silt Loam	180	40	900	180
Balochistan	Loamy Sand	42	30	900	42

2.7 Analytical Metrics:

2.7.1 Frequency Distribution Analysis:

A variable’s frequency distribution is determined using the frequency distribution analysis approach. In this thesis, the variable is effective rain, just want to find out if there are any disparities in frequency distribution among Pakistan’s provinces. Skewness and kurtosis will be used to differentiate the frequency distribution as shown in figures 2.10 and 2.11 respectively.

Skewness is a measure of the asymmetry of a distribution. A distribution is said to be asymmetrical if its left and right sides are not mirror reflections of each other. The skewness of a distribution might be right (or positive), left (or negative), or zero. The length of a right-skewed distribution is greater on the right side of its peak, whereas the length of a left-skewed distribution is greater on the left side of its peak.

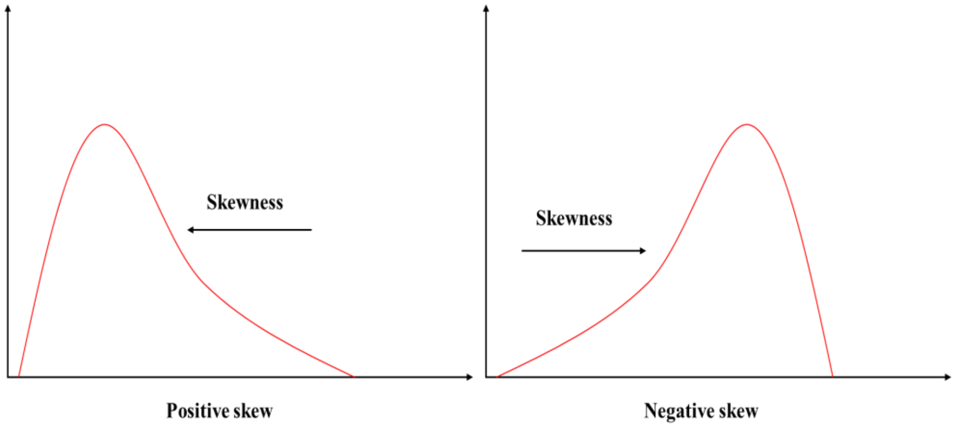


Figure 2.10 Positive and negative skew

Kurtosis is a metric that indicates how “taily” a distribution is. The frequency with which outliers occur is defined as tailness as shown in figure 2.11. Excess kurtosis is the tailedness of a distribution compared to a normal distribution.

- Mesokurtic distributions have medium kurtosis (medium tails).
- Platykurtic distributions have low kurtosis (thin tails).

- Leptokurtic distributions have a high kurtosis (fat tails).

The tapering ends on either side of a distribution are known as tails. They demonstrate the chance or frequency of values that are considerably more or less than the mean. Tails, in other words, represent how frequently outliers occur.

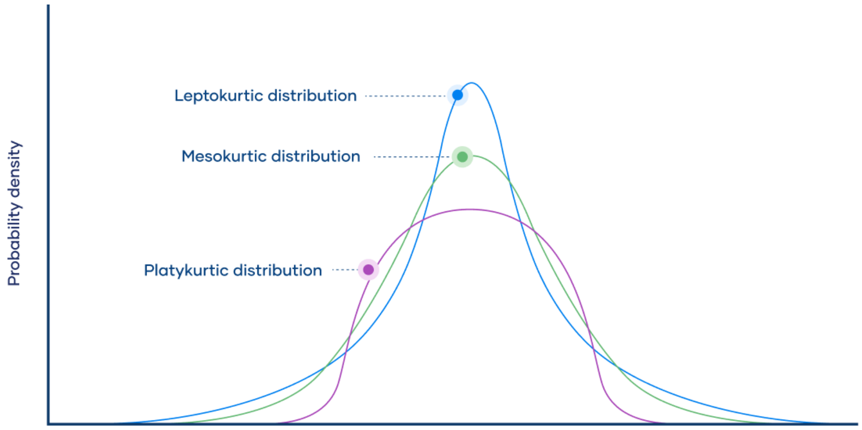
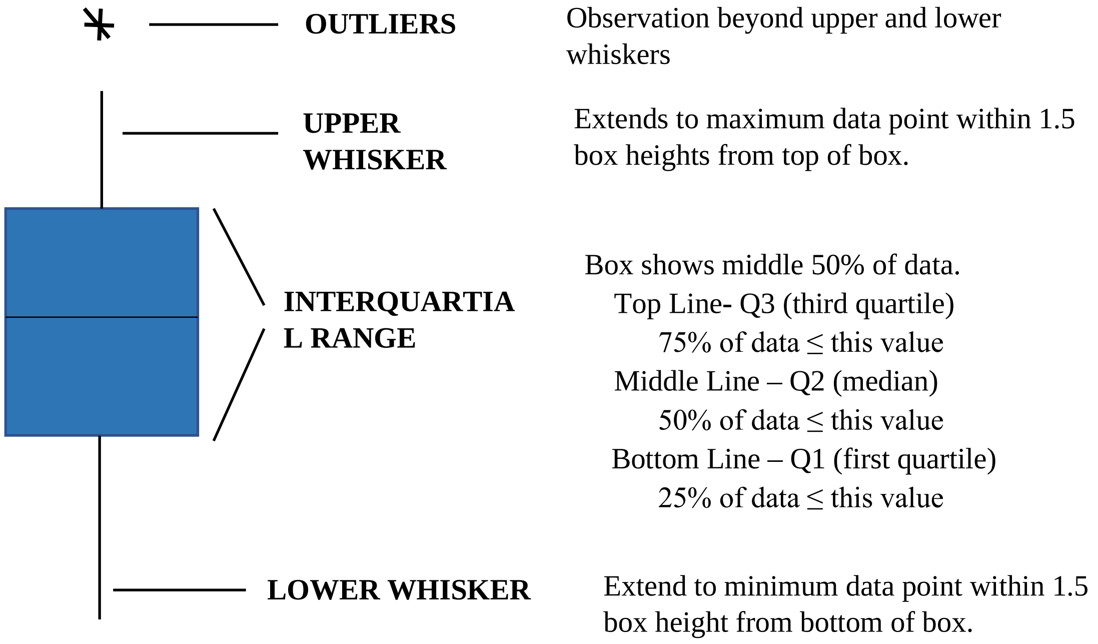


Figure 2.11 Types of kurtoses

2.7.2 Interquartile Range Analysis:

The interquartile range determines where a data set's "middle fifty" is placed. Whereas a range represents the beginning and end of a collection, an interquartile range represents the location of the majority of the values. The larger the IQ range, the more dispersed the data and the bigger the disparity between them. Figure 2.12 depicts a detailed explanation.



Observation beyond upper and lower whiskers

Extends to maximum data point within 1.5 box heights from top of box.

Box shows middle 50% of data.
Top Line- Q3 (third quartile)
75% of data ≤ this value
Middle Line – Q2 (median)
50% of data ≤ this value
Bottom Line – Q1 (first quartile)
25% of data ≤ this value

Extend to minimum data point within 1.5 box height from bottom of box.

Figure 2.12 Descriptive chart of interquartile range

2.7.3 Time Series Analysis:

Time series analysis is a technique for analysing a group of data points accumulated over time. Instead of gathering data points intermittently or randomly, time series analyzers capture data points at fixed intervals throughout a defined timeframe. In this thesis , the crop growing season time series ws break into three parts (beginning, middle, and late). Figure 2.13 displays a time series study of an ER abnormality.

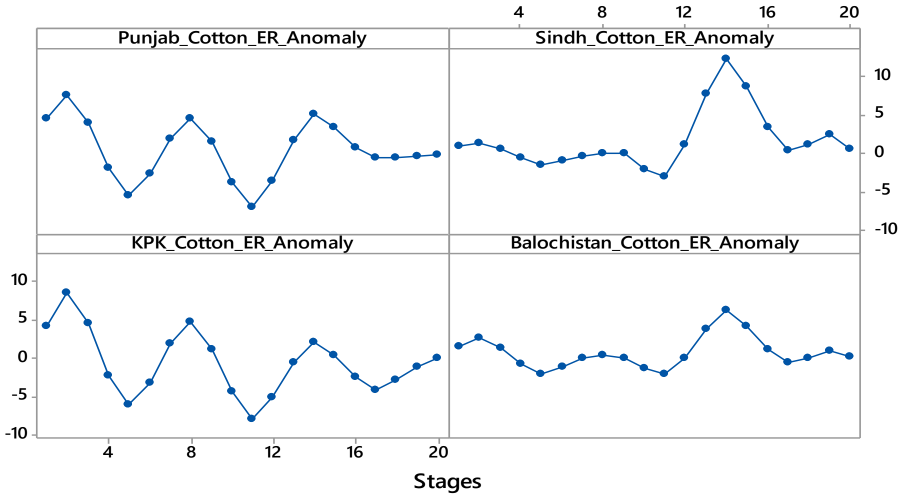


Figure 2.13 Time series analysis graph

2.7.4 CDF Base Analysis:

To depict the data points in your sample in decreasing to increasing percentiles, use an empirical cumulative distribution function (CDF) graphic. You may determine percentiles and other distribution properties using these graphs, which need continuous data. Another term for this function is empirical CDF or ECDF. If you assess the same property in many samples, you may use empirical CDF plots to compare the sample distributions. There are two forms of CDF analysis: exponential and logarithmic.

If the CDF curve of a function remains within the same range for larger percentage values on both the positive and negative sides, the function is more exponential or logarithmic. On the other hand, if the CDF curve gradually transitions from one range to another, the function is more logarithmic, shifting from positive to negative values.For functions that are more logarithmic, their CDF curve will exhibit a stronger presence from zero to larger values on the positive side. Conversely, for functions that are more exponential, their CDF curve will be more dominant at lower values.

Please note that the rearranged version maintains the original meaning of your statement, but it may be beneficial to provide additional context or specific equations if you have them.

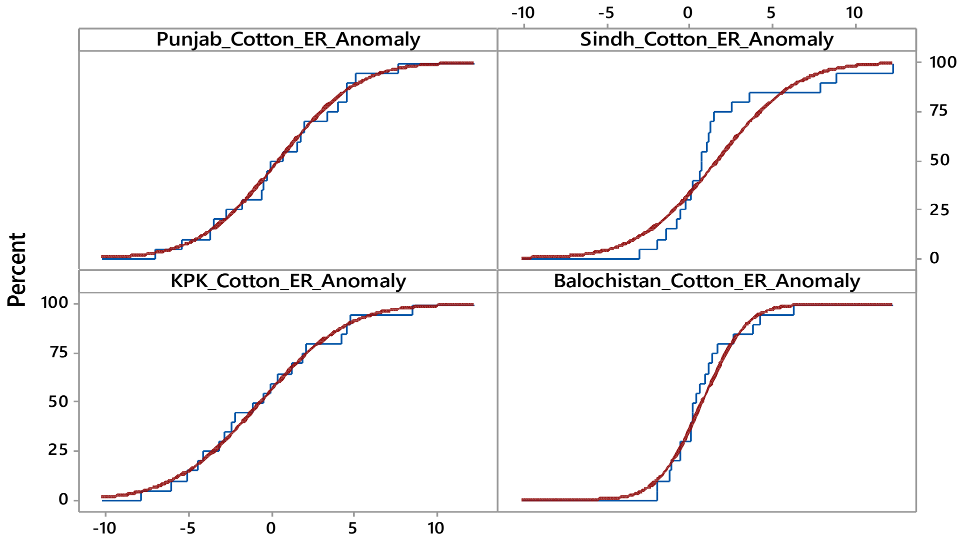


Figure 2.14 CDF base analysis graph

CHAPTER 3

3 RESULTS AND DISCUSSION

3.1 Cotton Season:

3.1.1 Frequency Distribution Analysis of ER, ETc and IR for Cotton Season:

Effective Rain (ER):

Beginning with the Punjab , the graph for Punjab ER anomaly for cotton season is negatively skewed, indicating that there are higher frequencies or occurrences of data on the positive side. It included shifting the data to the positive side and increasing the number of occurrences in which the rain increased largely from 5 mm/Dm up to 7.5 mm/Dm in magnitude. This suggests that there will be more positive occurrences of rain in the future, and it is mesokurtic, which means that the occurrence of mean ER is normal, so either ER will be close to normal or positive ER will be more common for cotton season.

The graph for the Sindh ER anomaly for cotton season shows that it is positively skewed which means there are more frequencies or occurrences of data on the negative side. Which included that the data will be shifted to the negative side, but the magnitude of the negative occurrences is 2.5 mm/Dm which is low as compared to the Punjab data which means there will be more negative occurrences in which the rain will be decreased but, in less magnitude, so the effect will be also less. It is leptokurtic which means that the occurrence of mean ER will be high so either ER will be strongly near to normal or negative ER will be more frequent.

Now comes the graph for the Khyber Pakhtunkhwa ER anomaly. It is positively skewed which means there are more frequencies or occurrences of data on the negative side. Which included that the data will be shifted to the negative side, but the magnitude of the negative occurrences are -5 mm/Dm and -7.5 mm/Dm which is just like Punjab data but in negative values. Which means there will be more negative occurrences in which the rain will be decreased and in high magnitude which means the ER will frequently decrease in the future. It is mesokurtic which means that the occurrence of mean ER is normal so either ER will be near normal or negative ER will be more frequent for cotton season.

In the end, the graph for Balochistan ER anomaly is negatively skewed which means there are more frequencies or occurrences of data on the positive side. Which included that the data will be shifted to the positive side, but the magnitude of the negative occurrences is up to 5 mm/Dm which is low as compared to the Punjab data which means there will be more positive occurrences in which the rain will be increased but, in less magnitude, so the effect will be also less. It is leptokurtic which means that the occurrence of mean ER will be high so either ER will be strongly near to normal or positive ER will be more frequent.

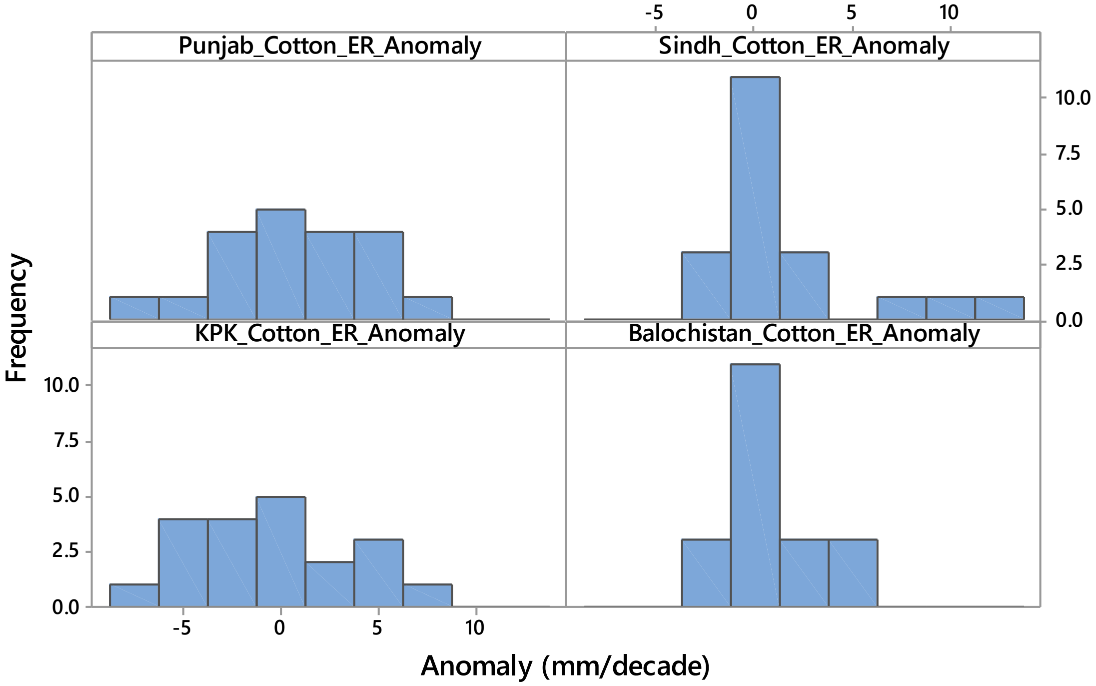


Figure 3.1 Frequency distribution chart of ER for the cotton season

Crop Water Requirement (ETc):

Starting from the Punjab in the graph for the Punjab ETc anomaly for cotton season is positively skewed which means there are more frequencies or occurrences of data on the negative side. Which included that the data will be shifted to the negative side but the magnitude of the ETc occurrence is mostly 2.5 mm/Dm which is very low so the effectiveness will also be less. And it is mesokurtic which means that the normal values occurrences of

ETc will be normal so it concludes that the graph will be either normal or negative ETc will be frequent.

The graph for the Sindh ETc anomaly for cotton season shows that it is negatively skewed which means there are more frequencies or occurrences of data on the positive side. Which means that the data will be shifted to the positive side and the magnitude of the positive occurrences is up to 7.5 mm/Dm which is high this means there will be more positive occurrences in which the rain will be increased in the future so the effect will also be high. It is platykurtic which means the occurrences of mean ETc are normal which means positive ETc is more frequent. For cotton season.

Now comes the graph for the Khyber Pakhtunkhwa ETc anomaly for cotton season. It is positively skewed which means there are more frequencies or occurrences of data on the negative side. Which included that the data will be shifted to the negative side, the magnitude of the negative occurrences is 2.5 mm/Dm which is just like Punjab ETc data. Which means there will be more negative occurrences in which the crop water requirement will be decreased but in low magnitude which means the effect will also be less. It is leptokurtic which means that the occurrences of mean ETc are high so either crop water requirement will be strongly near to normal or negative ETc will be more frequent for cotton season .

In the end, the graph for the Balochistan ETc anomaly for cotton season is Positively skewed which means there are more frequencies or occurrences of data on the negative side. Which included that the data will be shifted to the negative side, but the magnitude of the negative occurrences is up to 2.5 mm/Dm which is low just like Punjab and Khyber Pakhtunkhwa graphs. Which means there will be more negative occurrences in which the ETc will be increased but, in less magnitude, so the effect will be also less. It is platykurtic which means that the occurrences of mean ETc are low so negative ETc will be more frequent.

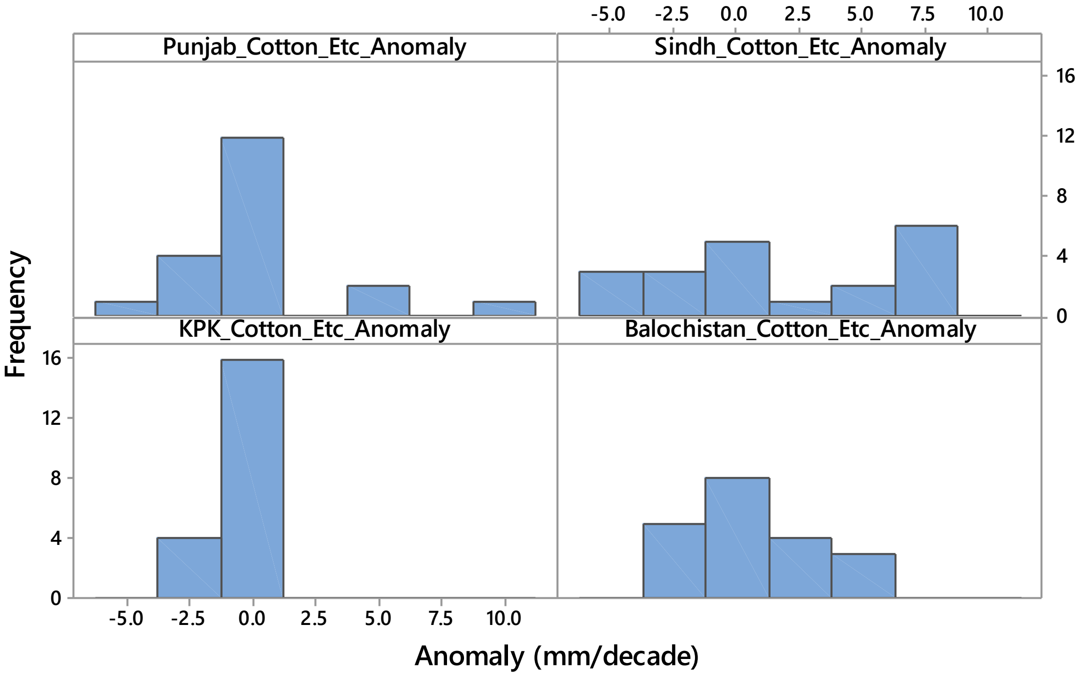


Figure 3.2 Frequency distribution chart of ETc for the cotton season

Irrigation Requirement (IR):

Starting from the Punjab in the graph for Punjab IR anomaly for cotton season is positively skewed which means there are more frequencies or occurrences of data on the negative side. Which included that the data will be shifted to the negative side and the magnitude of the negative occurrence is also high from 5 mm/Dm to 12.5 mm/Dm which means that in the future there will be a decrease in IR in Punjab. It is mesokurtic which means that the mean values occurrences of IR will be normal so it concludes that the graph will be either near to normal or negative IR will be frequent.

The graph for the Sindh IR anomaly for cotton season is negatively skewed which means there are more frequencies or occurrences of data on the positive side. Which included that the data will be shifted to the positive side and there will be more number occurrences in which the IR will increase mostly for 5 mm/Dm up to 12.5 mm/Dm in magnitude which is just like Punjab but in positive values that means in future there will be increased in IR in very high magnitude and it is platykurtic which means that the normal IR values will be very less so it concludes that positive IR will be more frequent.

Now comes the graph for the Khyber Pakhtunkhwa IR anomaly for cotton season. It is negatively skewed which means there are more frequencies or occurrences of data on the positive side. Which included that the data will be shifted to the positive side, and the magnitude of the negative occurrences is 5 mm/Dm .which means there will be more positive occurrences in which the IR will be increased but in low magnitude which means the effect will also be less and it is leptokurtic which means that the mean IR values will be very high so the graph will be strongly near to normal or positive IR will be frequent.

In the end, the graph for Balochistan IR anomaly for cotton is negatively skewed which means there are more frequencies or occurrences of data on the positive side. Which included that the data will be shifted to the positive side, but the magnitude of the positive occurrences is up to 5 mm/Dm which is low just like Sindh data. Which means there will be more positive occurrences in which IR will be increased but, in less magnitude, so the effect will be also less, and it is mesokurtic which means the mean value occurrence of IR will be normal so which means either it will be near to normal or positive IR will be more frequent.

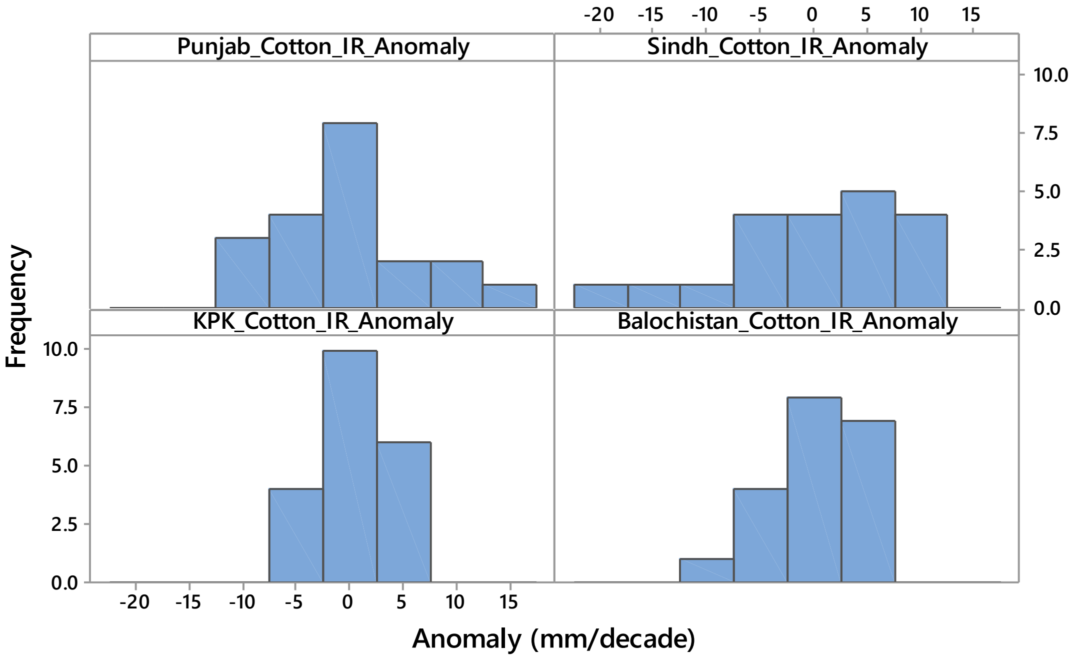


Figure 3.3 Frequency distribution chart of IR for the cotton season

3.1.2 Interquartile Range Analysis of ER, ETc and IR for Cotton Season:

Effective Rain (ER):

Starting from the IQ Range analysis of ER for cotton season in the figure 3.4 shows that Punjab and Khyber Pakhtunkhwa are more scattered as compared to Balochistan and Sindh which is determined by the values of IQ Range of Punjab and Khyber Pakhtunkhwa (6.3 mm/Dm and 5.9 mm/Dm) that is higher as compared to the IQ Range of Balochistan and Sindh (2.7 mm/Dm and 2.2 mm/Dm) respectively so the more the higher value of IQ Range the more the anomaly data will be scattered and will have big variation between them and that means that more erratic behavior of ER anomaly may be expected in Punjab and Khyber Pakhtunkhwa . While Sindh and Balochistan have the ER anomaly closer to the median values which renders them to exhibit a more consistent pattern.

Now the Khyber Pakhtunkhwa has a median (-0.8 mm/Dm) negative as compared to the other provinces which means that Khyber Pakhtunkhwa has negative values till the 50 percentile of the data which means that ER Anomaly for cotton season is more toward the negative side and by that most of the Khyber Pakhtunkhwa data will be in negative and will decrease in future and on other hand in Sindh Balochistan and Punjab the median (0.6 mm/Dm, 0.2 mm//Dm and 0.3 mm//Dm) is positive so the most of the values of ER anomaly will be on the positive side so ER will either remain stable or slightly increase in future.

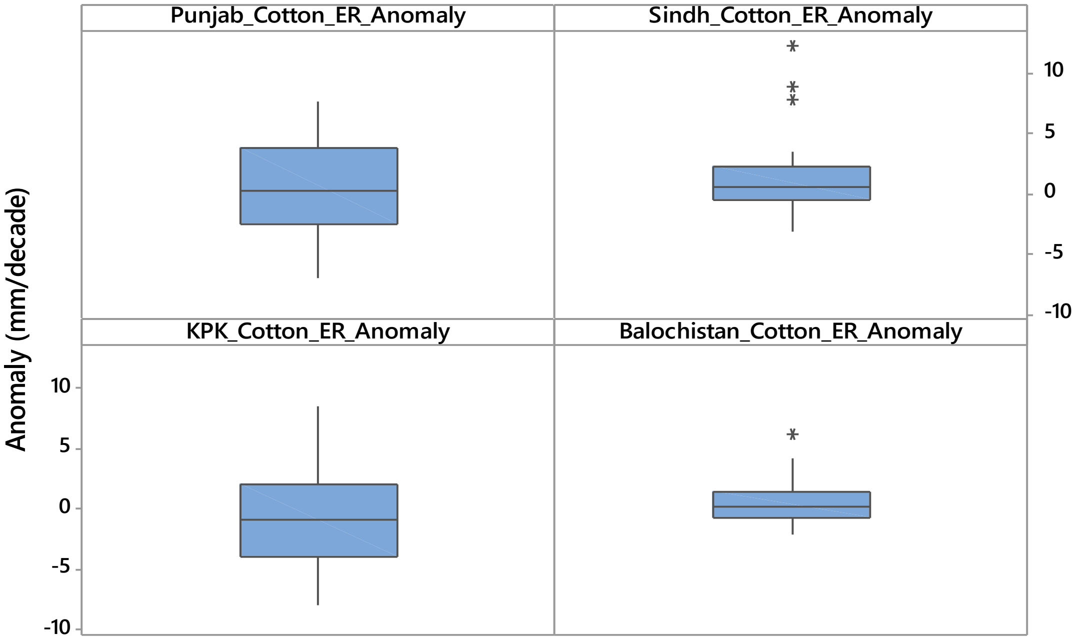


Figure 3.4 Interquartile range chart of ER for the cotton season

Table 3.1 IQ range and median of ER for the cotton season

Provinces	**Median**	**IQ Range**
Punjab	0.3	6.3
Sindh	0.6	2.7
Khyber Pakhtunkhwa	-0.8	5.9
Balochistan	0.2	2.2

Crop Water Requirement (ETc):

IQ Range analysis of ETc for cotton season in figure 3.5 shows that Sindh and Balochistan are more scattered as compared to the Punjab and Khyber Pakhtunkhwa which is determined by the values of IQ Range of Sindh and Balochistan (8.3 mm/Dm and 3.6 mm/Dm) that is high then the IQ Range of Punjab and Khyber Pakhtunkhwa (1.65 mm/Dm and 0.9 mm/Dm) respectively so the more the higher value of IQ Range the more the graph will be scattered and that means that more erratic behavior of ETc of anomaly may be expected in Sindh and Balochistan. While Punjab and Khyber Pakhtunkhwa have the ETc anomaly closer to the median values which renders them to exhibit a more consistent pattern.

Now all four of the provinces have a median negative which means that all provinces have negative values till the 50 percentile of the data that means that the ETc anomaly is more toward the negative side and by that, most of the data will be negative so ETc will decrease in future.

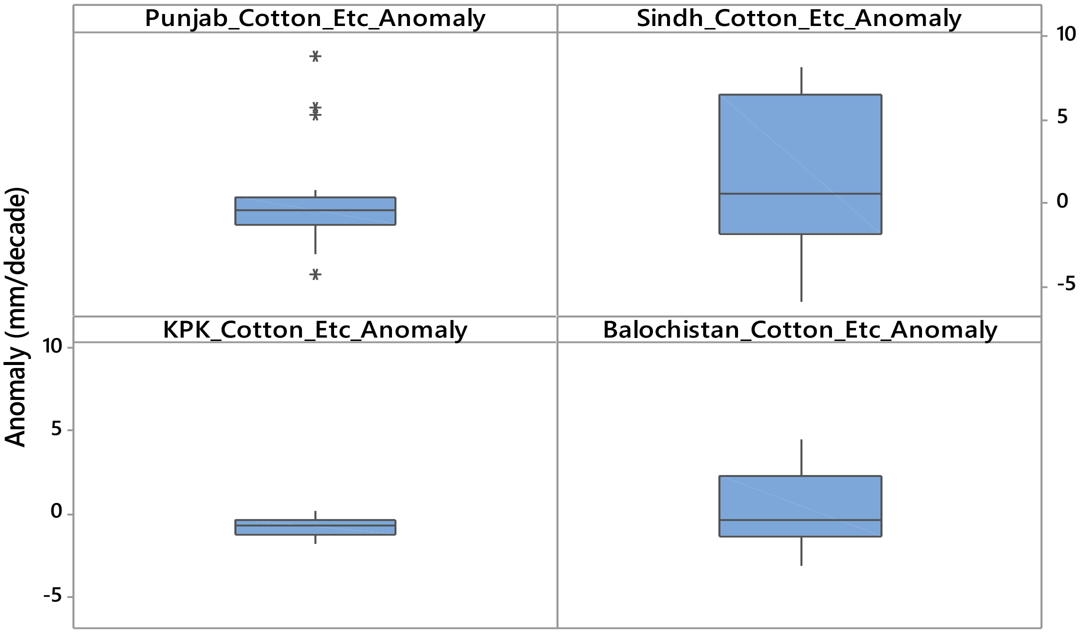


Figure 3.5 Interquartile range chart of ETc for the cotton season

Table 3.2 IQ range and median of ETc for the cotton season

Provinces	**Median**	**IQ Range**
Punjab	-0.35	1.65
Sindh	-1.7	8.3
Khyber Pakhtunkhwa	-0.6	0.9
Balochistan	-0.2	3.6

Irrigation Requirement (IR):

In the IQ Range analysis of IR for cotton season in figure 3.6 shows that Punjab and Sindh are more scattered as compared to the Balochistan and Khyber Pakhtunkhwa which is determined by the values of the IQ Range of Punjab and Sindh (7.2 mm/Dm and 10.4 mm/Dm) that is higher as compared to the IQ Range of Balochistan and Khyber Pakhtunkhwa (5.3 mm/Dm and 4.6 mm/Dm) respectively so the more the higher value of IQ Range the more the graph will be scattered and that means that more erratic behavior of IR anomaly for cotton season may be expected in Punjab and Sindh. While Khyber Pakhtunkhwa and Balochistan have IR anomalies closer to the median values which render them to exhibit a more consistent pattern.

Now that Punjab and Balochistan have a median (-0.9 mm/Dm – 0.3 mm/Dm) negative as compared to Sindh and Khyber Pakhtunkhwa which means that Punjab and Balochistan have negative values till the 50 percentile of the data means that IR anomaly is more toward the negative side and by that most of the data of Punjab and Balochistan will be in negative and will decrease in future and on other hand in Sindh and Khyber Pakhtunkhwa the median (0.1 mm/Dm and 0 mm/Dm) is positive so the most of the values of IR anomaly will be on the positive side so IR will either remain stable or slightly increase in future.

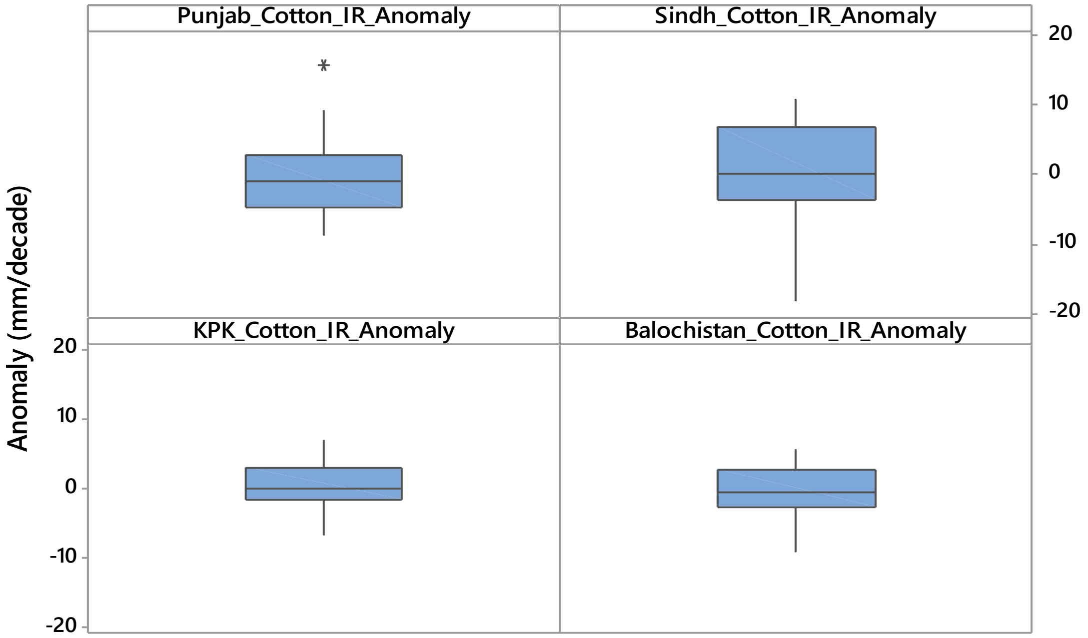


Figure 3.6 Interquartile range chart of IR for the cotton season

Table 3.3 IQ range and median of IR for the cotton season

Provinces	Median	IQ Range
Punjab	-0.9	7.2
Sindh	0.1	10.4
Khyber Pakhtunkhwa	0	4.6
Balochistan	-0.3	5.3

3.1.3 Time Series Analysis of ER, ETc, and IR for Cotton Season:

Effective Rain (ER):

In Sindh and Balochistan ER anomaly for cotton season as shown in figure 3.7 exhibit a significantly positive departure for the late stages of the cotton growing season also there is no significant change in ER anomaly for the cotton season during the early stages for Sindh and Balochistan provinces while for Punjab and Khyber Pakhtunkhwa the ER anomaly exhibit a periodic pattern for ER anomaly departure thereby balancing the deficiency from either side of the anomaly scale.

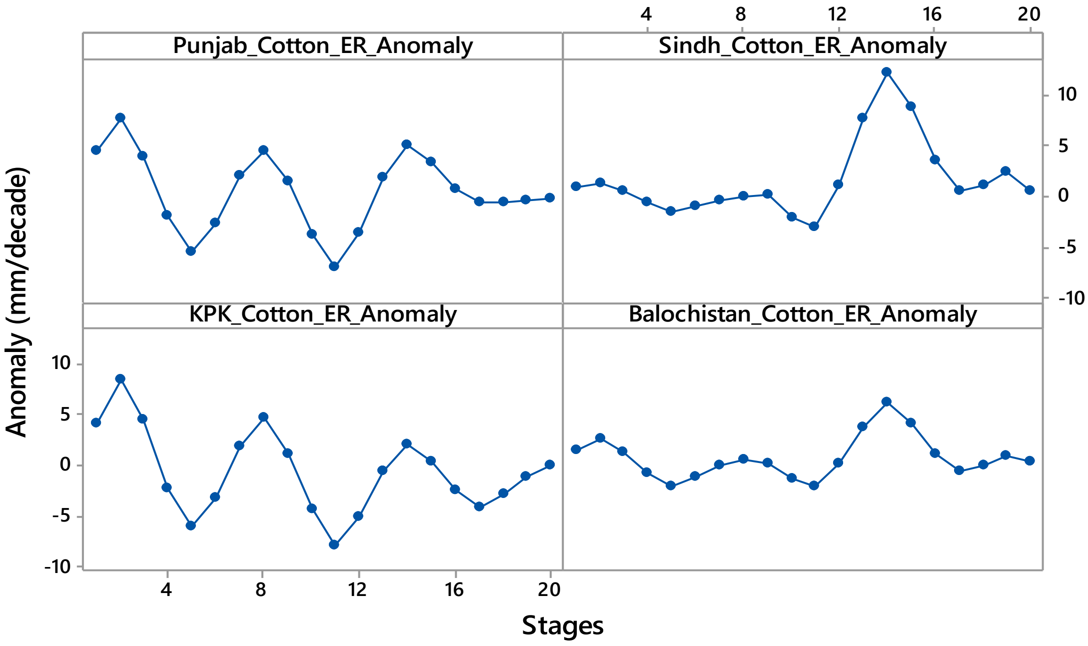


Figure 3.7 Time series chart of ER for the cotton season

Crop Water Requirement (ETc):

Of all the provinces ETc, anomaly remains nearly invariant during all stages of the cotton growing season in Khyber Pakhtunkhwa . However, a significant positive departure can be seen in the Punjab, Sindh, and Balochistan during the initial and middle stages of the cotton growing season thereby signaling the need for additional water resources to subside moisture deficiency.

In Punjab, Sindh, and Balochistan the ETc is also seen to reflect negative departure at the later stages of the cotton growing season. This means surplus water may be available for efficient use in these provinces in the projection period.

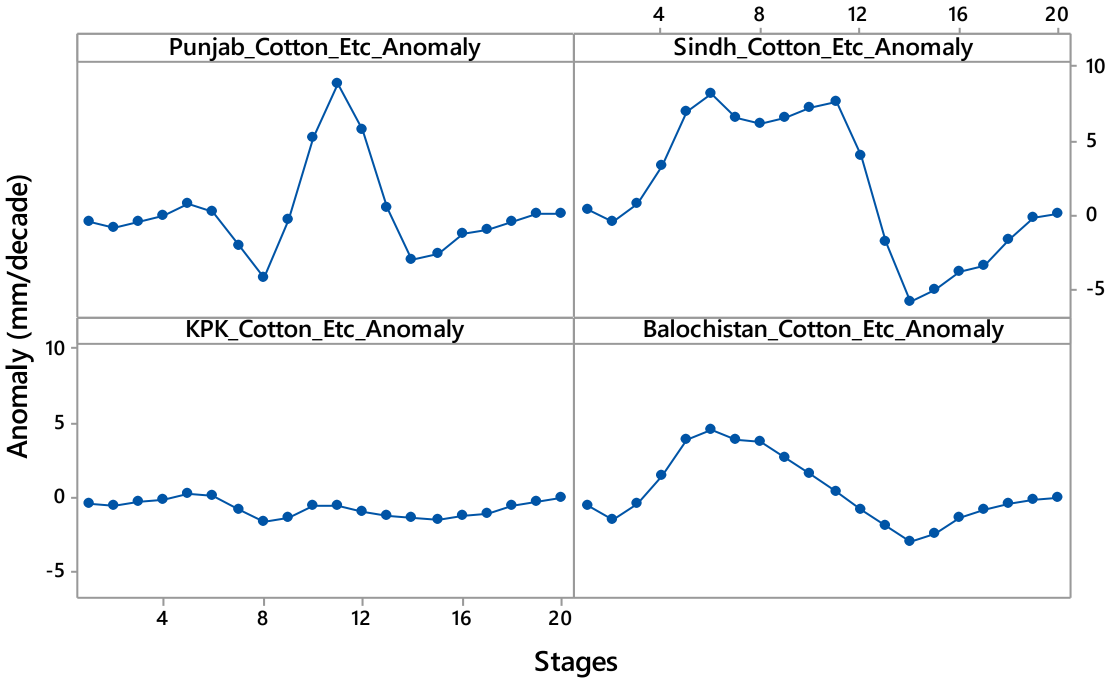


Figure 3.8 Time series chart of ETc for the cotton season

Irrigation Requirement (IR):

A similar pattern of ETc is reflected in IR anomalies for all the provinces in the cotton season. The Khyber Pakhtunkhwa and Punjab shows a similar pattern that is periodic for IR anomaly of cotton season. This means that both positive and negative departure prevails cyclically along the stages of the cotton growing season.

While on the other hand, Sindh and Balochistan are similar in pattern indicating higher IR from the initial to mid stages and smaller IR along the later stages of the cotton growing season also the highest positive departure of IR anomaly nearly reaches 20 mm/Dm is exhibited at the mid-stage of the cotton growing season in Punjab while highest negative that reaches to -20 mm/Dm is an exhibit at later stages cotton growing season in Sindh growing season this means that both Punjab and Sindh will require higher and lower IR at mid and later stages of the cotton growing season respectively.

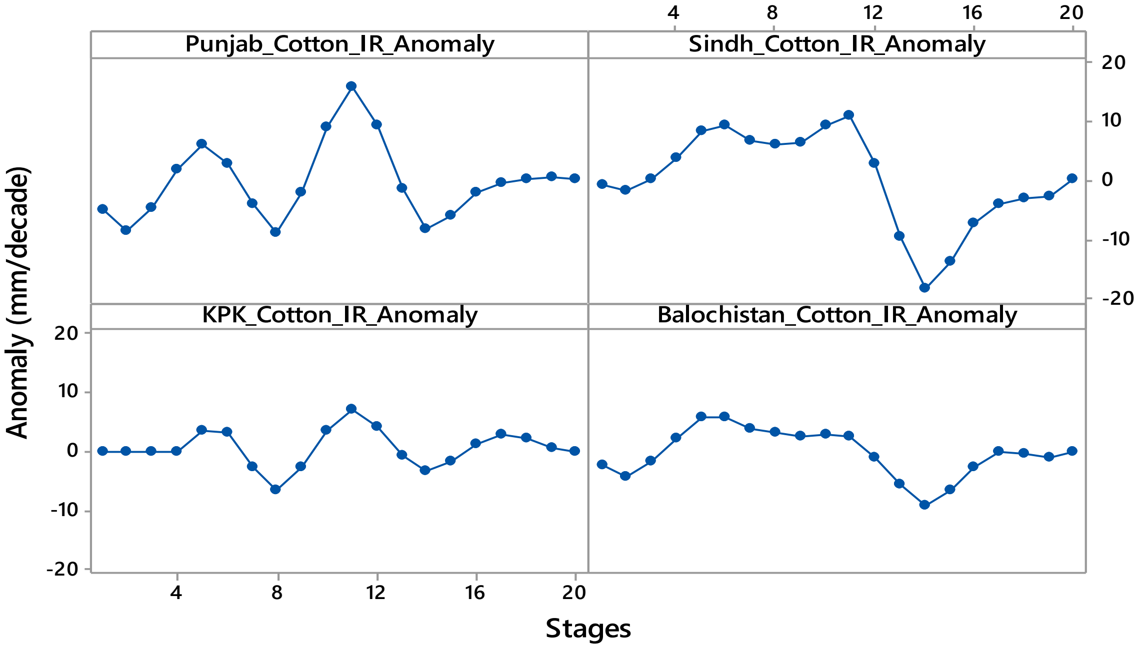


Figure 3.9 Time series chart of IR for the cotton season

3.1.4 CDF Base Analysis of ER, ETc and IR for Cotton Season:

Effective Rain (ER):

The Khyber Pakhtunkhwa cotton season exhibits an exponential increase in the negative departure that has more than 60 percent of ER anomaly on the negative side. This means that most of the departure of the ER in Khyber Pakhtunkhwa for cotton is negative on the other hand ER anomaly for Sindh has a 70 percent on the positive percentage of ER anomaly while Balochistan has a 60 percent of the positive percentage anomaly but an area under the curve for Balochistan is more as compared to Sindh due to the ER anomaly curve for Balochistan is close to zero. This means most of the departure of the ER anomaly in Balochistan for cotton is close to zero or less positive while Sindh is more toward the positive side. ER anomaly CDF for Punjab is different from the other provinces because its anomaly is 50 percent on the negative side and 50 percent on the positive side which means both positive and negative departure can equally prevail in the future for the cotton season in Punjab.

Now on the bases of shape parameters, Balochistan is more logarithmic as compared to Sindh which means it will remain in the same division for larger values of percentage which means it will be more persistent from zero to larger value on the positive side. On the other hand, Sindh is less logarithmic so it will gradually shift from one division to the other so it will more frequently at the larger value on the positive side of ER anomaly for the cotton season. While Punjab and Khyber Pakhtunkhwa are both less exponential and less logarithmic so it will gradually shift from one division to the other so it will be more frequent at the larger value on the both negative and positive side of ER anomaly for the cotton season.

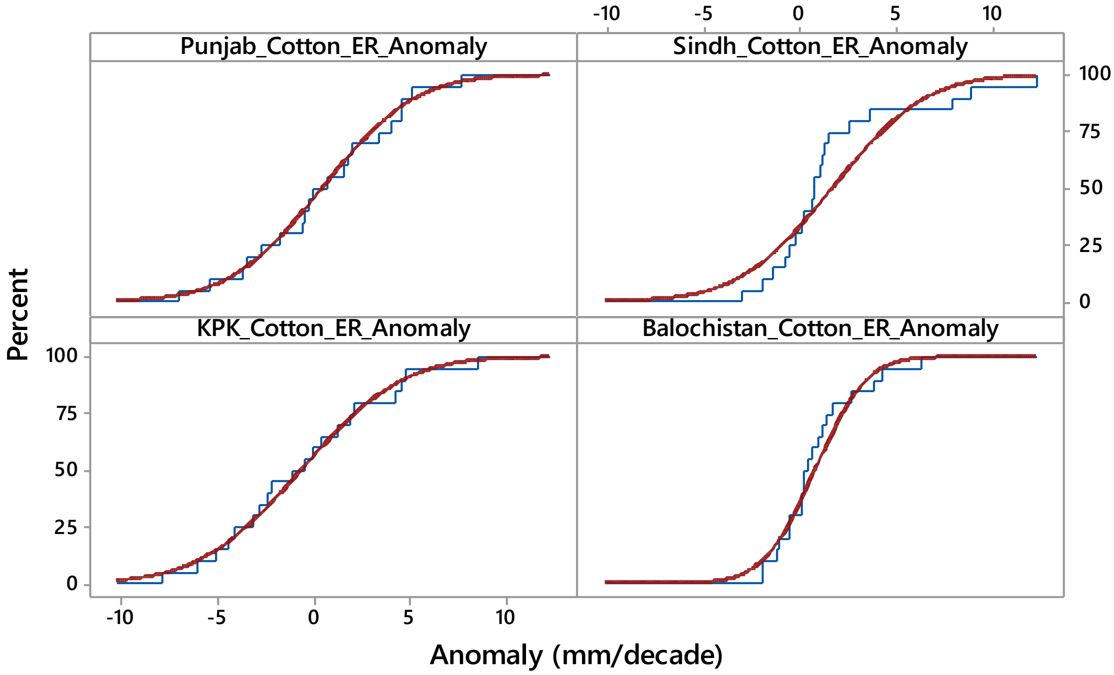


Figure 3.10 CDF base chart of ER for the cotton season

Crop Water Requirement (ETc):

Out of the ETc anomaly CDF for different provinces. The Khyber Pakhtunkhwa exhibits an exponential increase in the negative departure that is nearly close to zero and has more than 90 percent of ETc anomaly on the negative side while Punjab has more than 60 percent of ETc anomaly on the negative side. This means most of the departure of the ETc in Khyber Pakhtunkhwa for cotton is close to zero or slightly negative while Punjab is more toward negative on the other hand ETc anomaly for Sindh has 70 percent on the positive percentage of ETc anomaly while Balochistan has 55 percent of the positive percentage of anomaly This means most of the departure of the ETc in Balochistan for cotton is close to zero or slightly positive while Punjab is more toward the positive side.

Now on the bases of parameters Balochistan and Punjab is more logarithmic as compared to Sindh which means it will remain in the same division for larger values of percentage and it will be more persistent from zero to larger value on the positive side. On the other hand, Sindh is less logarithmic which means it will gradually shift from one division to the other so it will be more frequent at the larger value of ETc anomaly for the cotton season while Khyber Pakhtunkhwa is more exponential on the negative side than the other remaining provinces that means it will remain in the same division for larger values of percentage and it will be more frequent at smaller values on the negative side.

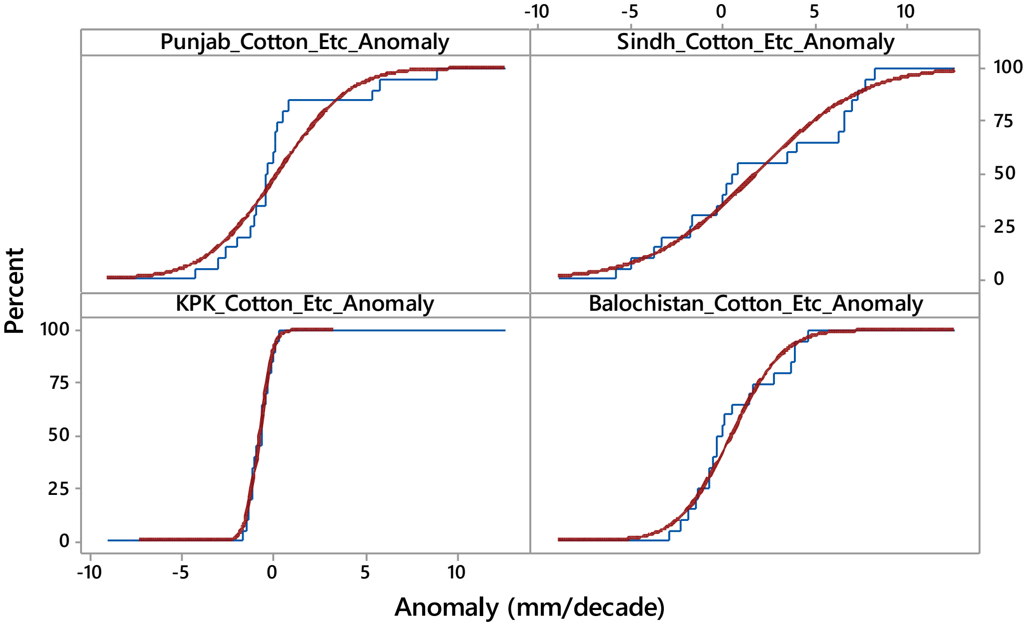


Figure 3.11 CDF base chart of ETc for the cotton season

Irrigation Requirement (IR):

The positive departure associated with IR anomalies for Khyber Pakhtunkhwa cotton season covers 60 percent of IR anomaly data as compared to the rest of the provinces. This means that in Khyber Pakhtunkhwa IR will be low or less irrigation will be required in the Khyber Pakhtunkhwa for the cotton season in the future. Although the rest of the provinces also show a larger volume of anomaly data along the positive departure yet their contribution to the negative departure is also high which means that both positive and negative departure can equally prevail in the future for the cotton season for the remaining provinces.

Now on the bases of parameters, Khyber Pakhtunkhwa is more logarithmic as compared to Sindh and Punjab which means it will remain in the same division for larger values of percentage and it will be more persistent from zero to larger value on the positive side. On the other hand, Sindh and Punjab are less logarithmic which means it will gradually shift from one division to the other so it will be more persistent from zero to larger value on the positive side of IR anomaly for the cotton season. Balochistan is more logarithmic and more exponential as compared to Punjab and Sindh. Which means it will have a more persistent from zero to a larger value on the positive and a less persistent from least to zero on the negative side of the IR anomaly for the cotton season.

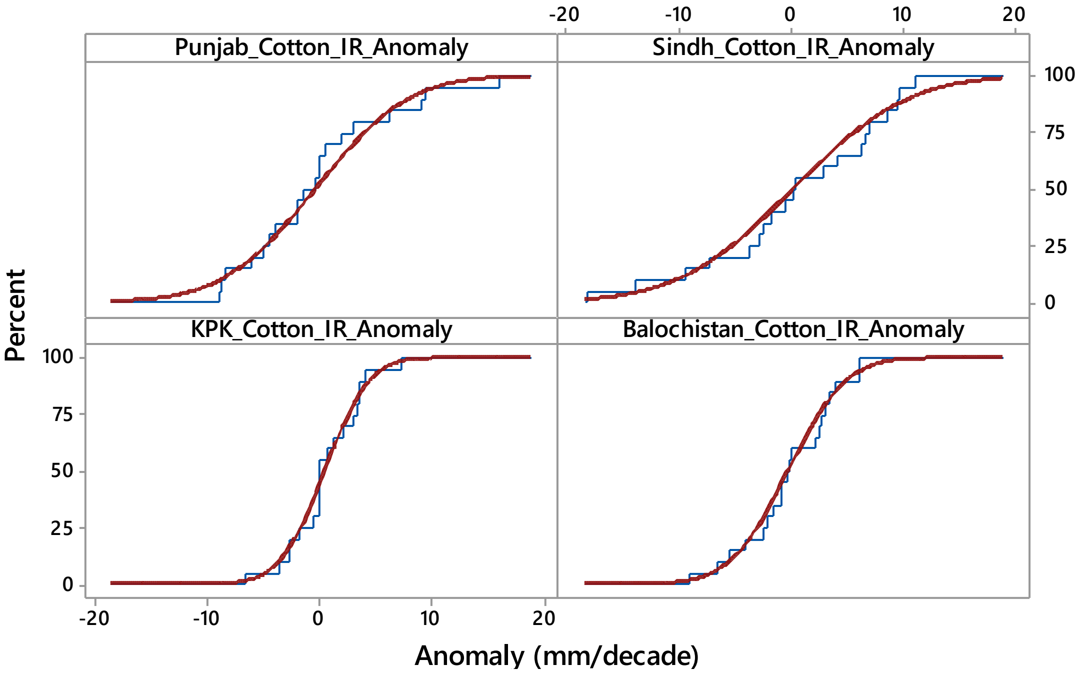


Figure 3.12 CDF base chart of IR for the cotton season

3.2 Wheat Season:

3.2.1 Frequency Distribution Analysis of ER, ETc and IR for Wheat Season:

Effective Rain (ER):

Starting from the graph of Punjab ER anomaly is negatively skewed which means there are more frequencies or occurrences of data on the positive side. Which means that the data will be shifted to the positive side and there will be more number occurrences in which the ER will increase mostly from 1 mm/Dm to 2 mm/Dm in magnitude. Which means there will be more positive occurrences in which the ER will be increased in the future. It is mesokurtic which means that the normal value occurrence of ER is normal which means either it will be near to normal or positive rain will be frequent.

The graph for the Sindh ER anomaly shows that it is positively skewed which means there are more frequencies or occurrences of data on the normal or slightly negative side. Which included that the data will slightly shift to the negative side which means there will be more negative occurrences in which the ER will decrease .it is mesokurtic which means the normal value occurrence of ER is normal which means either it will be near to normal or slightly negative.

Now comes the graph for the Khyber Pakhtunkhwa ER anomaly. It is positively skewed which means there are more frequencies or occurrences of data on the negative side. Which included that the data will be shifted to the negative side and the magnitude of the negative occurrences are up to -3 mm/Dm. Which means there will be more negative occurrences in which the ER will be decreased which means the rain will frequently decrease in the future. It is platykurtic which means that the normal ER values will be very less so which means the negative rain will be more frequent.

In the end, the graph for Balochistan ER anomaly shows that it is positively skewed which means there are more frequencies or occurrences of data on the normal or slightly negative side. Which means that the data will slightly shift to the negative side and the magnitude of the occurrences are either negative at 1 mm/Dm or remain normal. Which means there will be more occurrences in which the ER will either be normal or slightly decreases in the future.

It is leptokurtic which means that the normal value occurrence of ER is high which means either it will be near to normal or slightly negative.

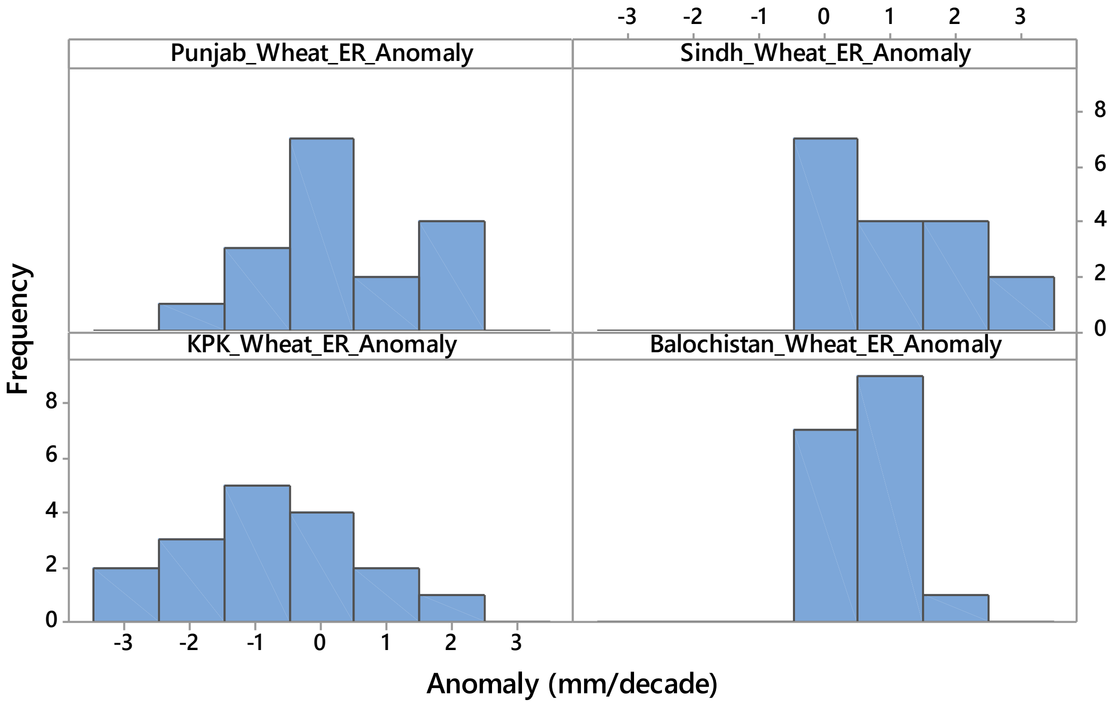


Figure 3.13 Frequency distribution chart of ER for the wheat season

Crop Water Requirement (ETc):

Starting from the Punjab graph for ETc anomaly is neither negatively skewed nor positively skewed so which means ETc for Punjab is near to normal and it is leptokurtic which means that the occurrence of mean ETc is higher than moderate so that means ETc will be strongly normal for the wheat season.

The graph for the Sindh ETc anomaly shows that it is negatively skewed which means there are more frequencies or occurrences of data on the positive side. Which included that the data will be shifted to the positive side and the magnitude of the positive occurrences are up to 1.5 mm/Dm which means there will be more positive occurrences in which the ETc will be increased in the future. It is platykurtic which means the occurrences of mean ETc are low which means positive ETc is more frequent.

Now comes the graph for the Khyber Pakhtunkhwa ETc anomaly. It is negatively skewed which means there are more frequencies or occurrences of data on the negative side. Which included that the data will be shifted to the negative side, and the magnitude of the negative occurrences is – 0.5 mm/Dm. Which means there will be more negative occurrences in which the ETc will be decreased and it is mesokurtic which means that the occurrences of mean ETc are normal so either ETc will be normal or negative ETc will be more frequent.

The graph for the Balochistan ETc anomaly shows that it is negatively skewed which means there are more frequencies or occurrences of data on the positive side. Which included that the data will be shifted to the positive side and the magnitude of the positive occurrences are up to 1.5 mm/Dm. Which means there will be more positive occurrences in which the ETc will be increased in the future. It is platykurtic which means the occurrences of mean ETc are low which means positive ETc is more frequent.

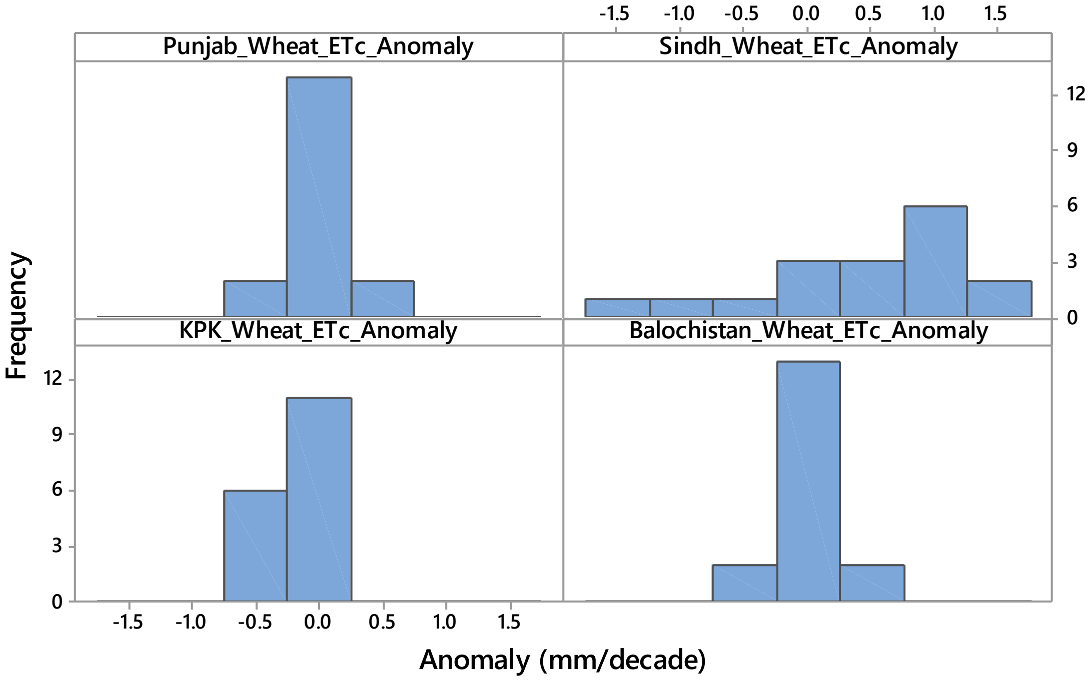


Figure 3.14 Frequency distribution chart of ETc for the wheat season

Irrigation Requirement (IR):

Starting from the Punjab graph of IR anomaly for wheat season is positively skewed which means there are more frequencies or occurrences of data on the normal or slightly negative side. Which means that the data will slightly shift to the negative side and the magnitude of the positive occurrence is 1 mm/Dm. Which means that in the future there will be a decrease in IR in the Punjab. And it is mesokurtic which means that the occurrence of mean IR is normal so either IR will be normal or negative IR will be more frequent.

The graph for the Sindh IR anomaly for wheat season is positively skewed which means there are more frequencies or occurrences of data on the negative side. Which means that the data will be shifted to the negative side in the future and there will be more number occurrences in which the IR will decrease from -1 mm/Dm to -2 mm/Dm in magnitude which means in the future there will be a decrease in irrigation requirement in Sindh. It is platykurtic which means that the mean IR values will be very less so negative IR will be more frequent.

Now comes the graph for the Khyber Pakhtunkhwa IR anomaly for wheat season. It is positively skewed which means there are more frequencies or occurrences of data on the normal or slightly negative side. Which included that the data will be shifted to the negative side. Which means there will be more negative occurrences in which the IR will decrease in the future. And it is leptokurtic which means that the occurrence of mean IR is high so either IR will be strongly normal or slightly negative IR will be more frequent.

In the end, the graph for Balochistan IR anomaly for wheat season is negatively skewed which means there are more frequencies or occurrences of data on the normal or slightly positive side. Which means that the data will slightly shift to the positive side. Which means there will be more positive occurrences in which the IR will increase in the future. And it is mesokurtic which means that the occurrence of mean IR is normal so either IR will be normal or slightly positive in the projection for wheat season.

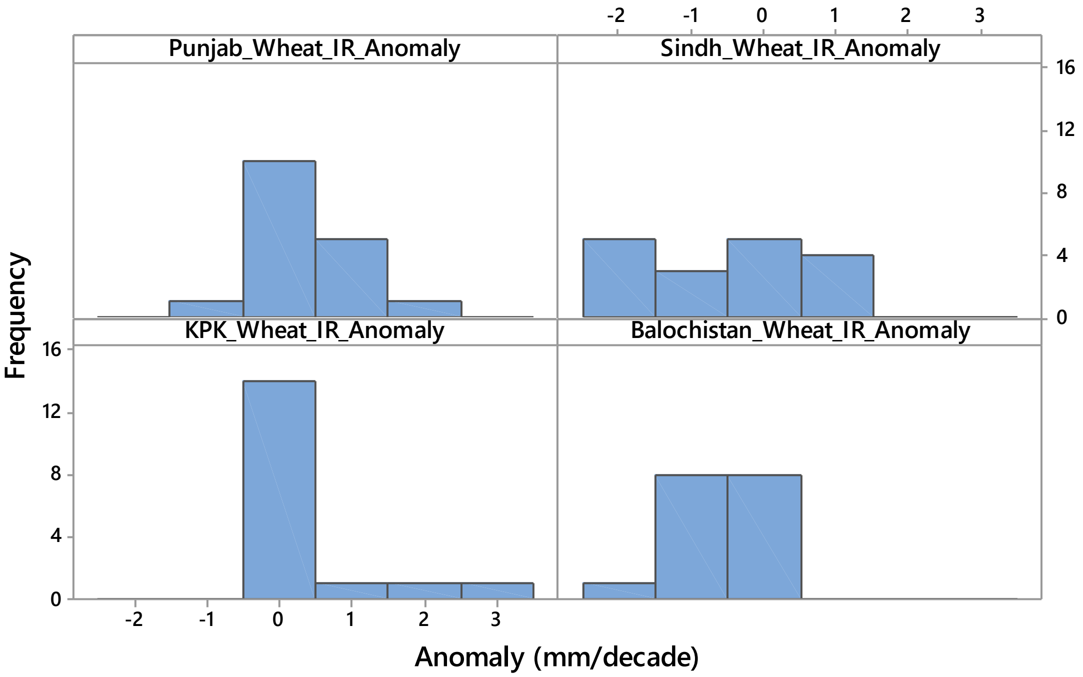


Figure 3.15 Frequency distribution chart of IR for the wheat season

3.2.2 Interquartile Range Analysis of ER, ETc and IR for Wheat Season:

Effective Rain (ER):

Starting from the IQ Range analysis of ER for wheat season in the graph for Punjab and Khyber Pakhtunkhwa and Sindh are more scattered as compared to Balochistan which is determined by the values of the IQ Range of Punjab, Khyber Pakhtunkhwa , and Sindh (2.1 mm/Dm, 1.9 mm/Dm and 1.7 mm/Dm) that is higher as compared to the IQ Range of Balochistan (1.1 mm/Dm) so the more the higher value of IQ Range the more the ER anomaly data will be scattered and will have big variation between them and that means more erratic behavior of ER of anomaly may be expected in Punjab and Khyber Pakhtunkhwa and Sindh. While in Balochistan the ER anomaly is closer to the median values which renders him to exhibit a more consistent pattern.

Now that Punjab and Khyber Pakhtunkhwa have a median (-0.3 mm/Dm and -0.8 mm/Dm) negative as compared to Sindh and Balochistan which means that Khyber Pakhtunkhwa and Punjab have negative values till the 50 percentile of the data means that

ER Anomaly is more toward the negative side and by that, most of the data of Khyber Pakhtunkhwa and Punjab will be in negative and hence it will decrease in future on other hand in Sindh Balochistan and Punjab the median is positive so the most of the values of ER anomaly for wheat season will be on the positive side so ER will either remain stable or increase in future.

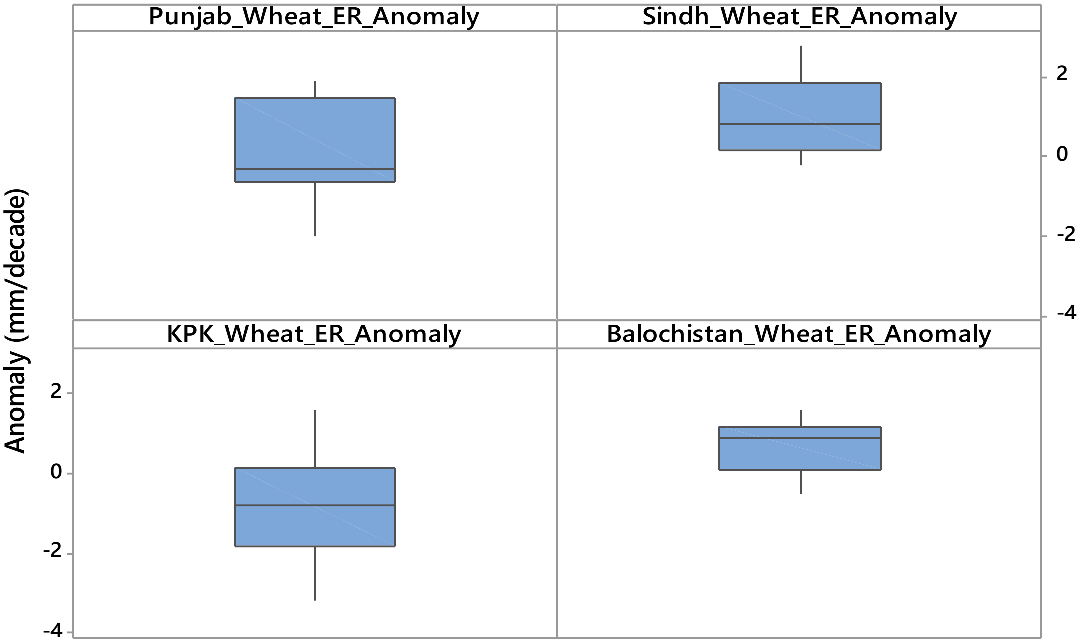


Figure 3.16 Interquartile range chart of ER for the wheat season

Table 3.4 IQ range and median of ER for the wheat season

Provinces	Median	IQ Range
Punjab	-0.3	2.1
Sindh	0.8	1.7
Khyber Pakhtunkhwa	-0.8	1.9
Balochistan	0.9	1.1

Crop Water Requirement (ETc):

Now comes the IQ Range analysis of ETc for wheat season , in the figure 3.17 shows that the anomaly data of Sindh is more scattered as compared to the Punjab, Khyber Pakhtunkhwa , and Balochistan which is determined by the values of the IQ Range of Sindh (0.9 mm/Dm) that is high then the IQ Range of Punjab and Khyber Pakhtunkhwa and Balochistan (0.2 mm/Dm, 0.3 mm/Dm and 0.3 mm/Dm) respectively so the more the higher value of IQ range the more the anomaly data will be scattered and will have big variation between them that means more erratic behavior of ETc of anomaly may be expected in Sindh. While Punjab, Khyber Pakhtunkhwa and Balochistan have the ETc anomaly closer to the median values which renders them to exhibit a more consistent pattern.

Now that only Khyber Pakhtunkhwa has a median (0.2 mm/Dm) in negative and close to zero which means that Khyber Pakhtunkhwa has negative values till the 50 percentile of the data which means ETc anomaly of Khyber Pakhtunkhwa for wheat season is more toward the negative side which means most of the data of Khyber Pakhtunkhwa will be negative and close to normal so ETc will either remain stable or slightly decrease in future but on the other hand, Punjab and Balochistan median (0 mm/Dm and 0.1 mm/Dm) is slightly positive so ETc of Punjab and Balochistan will either remain stable or slightly increases in future but in Sindh anomaly data median (0.7 mm/Dm) is more toward the positive side then Punjab and Balochistan so ETc of Sindh will increase in future.

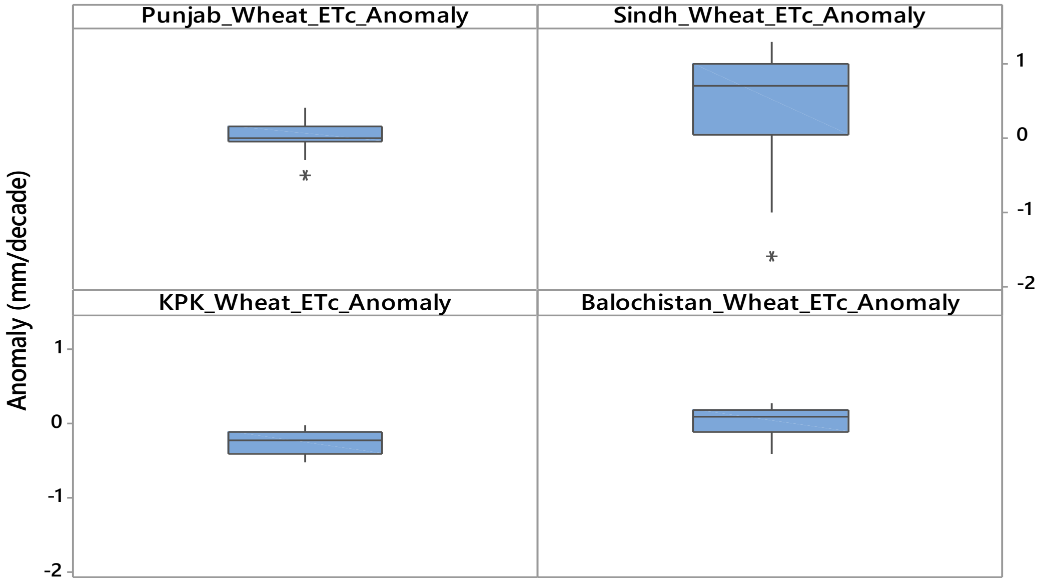


Figure 3.17 Interquartile range chart of ETc for the wheat season

Table 3.5 IQ range and median of ETc for the wheat season

Provinces	Median	IQ Range
Punjab	0	0.2
Sindh	0.7	0.9
Khyber Pakhtunkhwa	-0.2	0.3
Balochistan	0.1	0.3

Irrigation Requirement (IR):

At the end of the IQ Range analysis of IR for wheat season as figure 3.18 shows that the anomaly data of Sindh is more scattered as compared to the Punjab, Khyber Pakhtunkhwa , and Balochistan which is determined by the values of IQ Range of Sindh (2.2 mm/Dm) that is higher as compared to the IQ Range of Punjab, Khyber Pakhtunkhwa and Balochistan (0.8 mm/Dm, 0 mm/Dm and 1.0 mm/Dm) respectively so the more the higher value of IQ Range the more the anomaly data will be scattered and will have big variation between them and that means that more erratic behavior of IR of anomaly may be expected in Sindh. While in

Punjab, Khyber Pakhtunkhwa and Balochistan have the IR anomaly closer to the median values which renders them to exhibit a more constant pattern.

Now that Sindh and Balochistan have a median (-0.9 mm/Dm and - 0.3 mm/Dm) negative as compared to Punjab and Khyber Pakhtunkhwa which means that Punjab and Balochistan have negative values till the 50 percentile of the data means that IR anomaly is more toward the negative side and which means most of the data of Punjab and Balochistan will be in negative and will decrease in future but on other hand in Sindh and Khyber Pakhtunkhwa the median is null. Which is positive but normal so most of the values of IR anomaly for wheat season will either remain stable or slightly increase in the future.

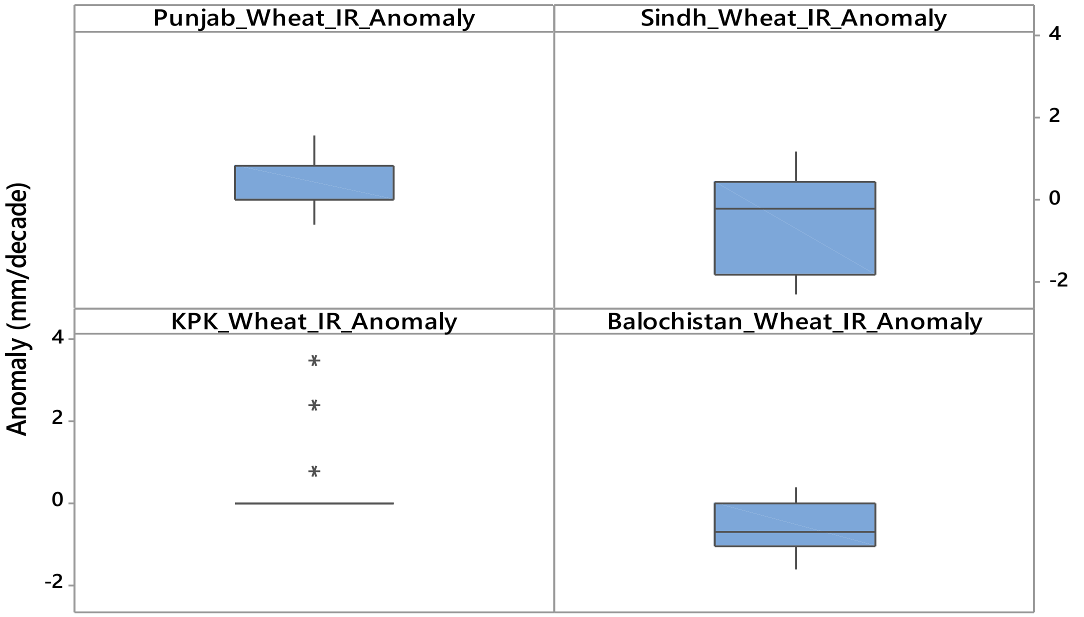


Figure 3.18 Interquartile range chart of IR for the wheat season

Table 3.6 IQ range and median of IR for the wheat season

Provinces	Median	IQ Range
Punjab	0	0.8
Sindh	-0.2	2.2
Khyber Pakhtunkhwa	0	0
Balochistan	-0.7	1.0

3.2.3 Time Series Analysis of ER, ETc and IR for Wheat Season:

Effective Rain (ER):

ER anomaly for wheat in Sindh and Balochistan is positive or zero in a cyclic manner and hence indicates an increase or stability in ER of the wheat season in Sindh and Balochistan. On the other hand, Punjab and Khyber Pakhtunkhwa both exhibit positive and negative departure in ER anomaly of wheat which indicates an increase of supply in the early stages and a decrease thereafter at the later stages of the wheat season.

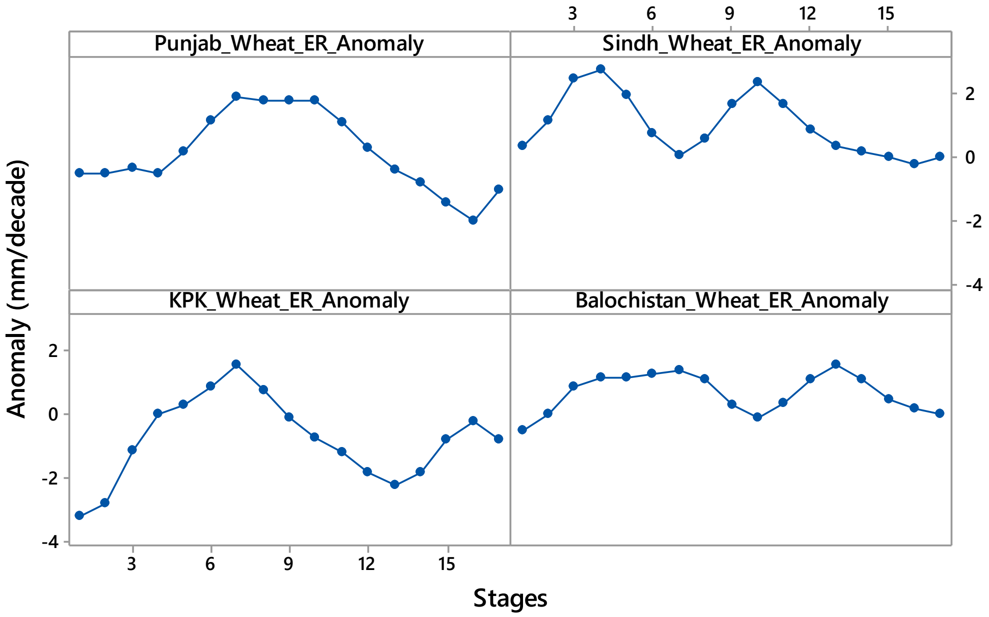


Figure 3.19 Time series chart of ER for the wheat season

Crop Water Requirement (ETc):

OF all the provinces the ETc anomaly for wheat season in Sindh exhibits some projected increase in a majority of the stages while on the other hand, the remaining provinces show near to stable anomaly which means the ETc will neither increase nor decrease significantly on the projection period for all the stages in wheat season.

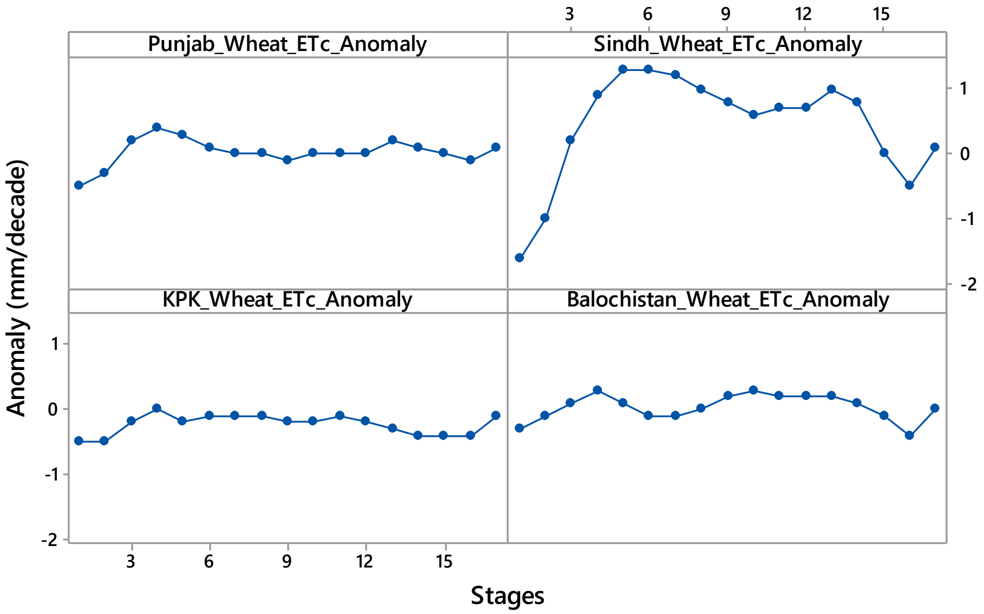


Figure 3.20 Time series chart of ETc for wheat season

Irrigation Requirement (IR):

In the IR anomaly for wheat season, the Khyber Pakhtunkhwa requires surplus water during the initial stages while for the rest of the stages, it does not require any irrigation water in the projection. For Punjab, surplus irrigation is required in the initial and later stages while during the middle stages, no Irrigation is required. The pattern of IR for Sindh and Balochistan is reversed as it shows an opposite pattern in both positive and negative anomalies of IR in the projection.

Although there is positive ETc in Sindh in the initial stages of the wheat season, the IR is negative which can be attributed in Sindh due to the positive departure of ER during the wheat season.

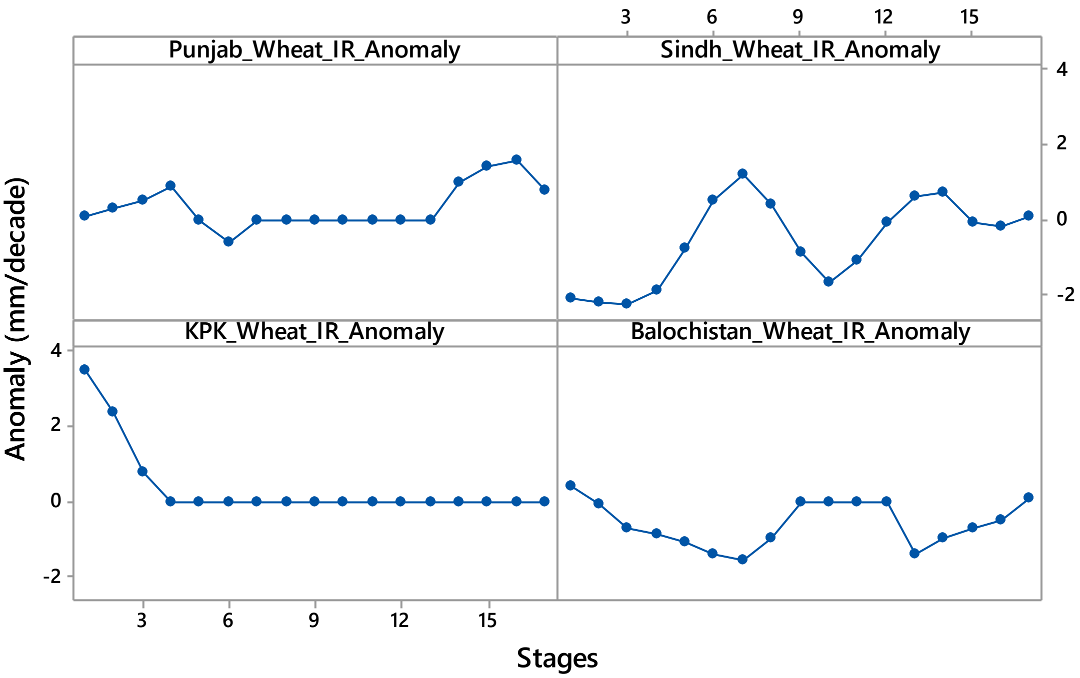


Figure 3.21 Time series chart of IR for the wheat season

3.2.4 CDF Base Analysis of ER, ETc and IR for Wheat Season:

Effective Rain (ER):

The Khyber Pakhtunkhwa wheat season exhibits an exponential increase in the negative departure that has more than 70 percent of ER anomaly on the negative side. This means that most of the departure of the ER in Khyber Pakhtunkhwa for the wheat season is negative on the other hand ER anomaly for Sindh and Balochistan has an 85 percent on the positive percentage of ER anomaly This means most of the departure of the ER anomaly in Balochistan and Sindh is more toward the positive side. ER anomaly CDF for Punjab is different from the other provinces because its anomaly is 50 percent on the negative side and 50 percent on the positive side which means both positive and negative departure can equally prevail in the future for the wheat season in Punjab.

Now on the bases of parameters, Balochistan is more logarithmic as compared to the other remaining provinces which means it will remain in the same division for larger values of percentage which means it will be more persistent from zero to larger values. On the other hand, the remaining provinces will have a more frequent at the larger value of ER anomaly for the wheat season.

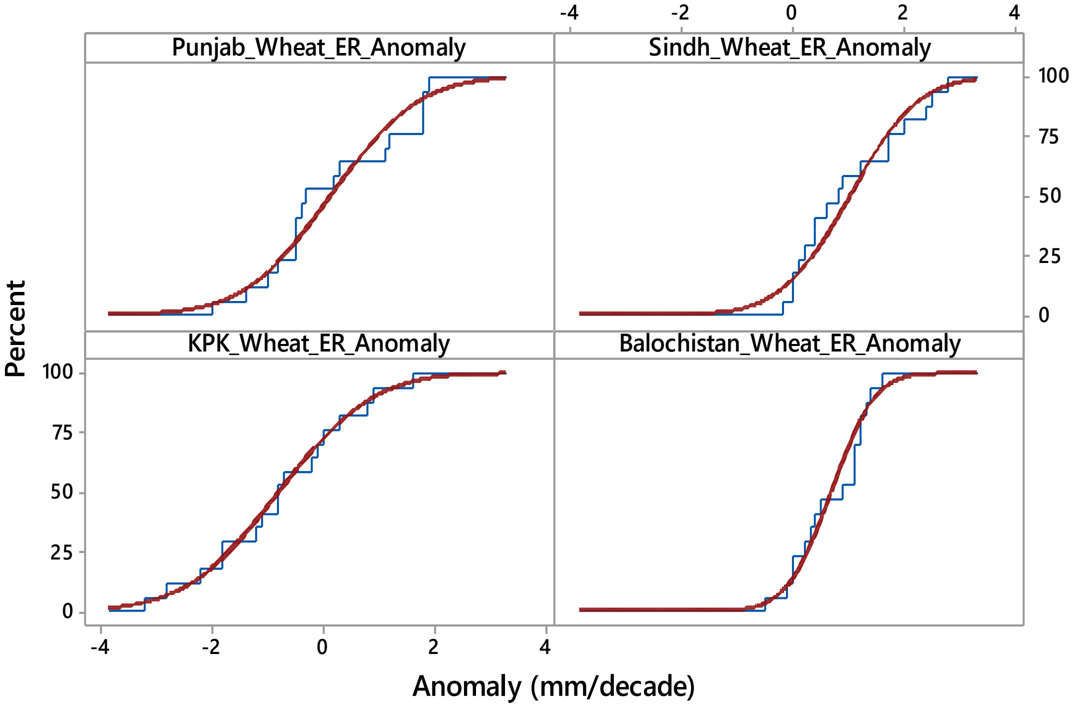


Figure 3.22 CDF base chart of ER for the wheat season

Crop Water Requirement (ETc):

Out of the ETc anomaly CDF for wheat season of different provinces. The Khyber Pakhtunkhwa exhibits an exponential increase in the negative departure that is nearly close to zero and has more than 95 percent of ETc anomaly on the negative side. This means most of the departure of the ETc in Khyber Pakhtunkhwa for the wheat season is close to zero or slightly negative. On the other hand, the ETc anomaly for wheat season of Sindh has a 70 percent on the positive percentage of ETc anomaly while Balochistan has a 60 percent of positive departure that is nearly close to zero or slightly positive. This means most of the departure of the ETc in Balochistan for wheat is close to zero or slightly positive while Sindh is more toward the positive side. ETc anomaly CDF for Punjab is different from the other provinces because its anomaly is 50 percent on the negative side and 50 percent on the positive side which means both positive and negative departure can equally prevail in the future for the wheat season in Punjab.

Now on the bases of shape parameters Balochistan and Punjab is more logarithmic as compared to Sindh which means they will remain in the same division for larger values of percentage and it will be more persistent from zero to a larger value. On the other hand, Sindh will have more persistent at the larger value of ETc anomaly for the wheat season while Khyber Pakhtunkhwa is more exponential on the positive side than the other remaining provinces which means it will remain in the same division for larger values of percentage and it will be more frequent at smaller values.

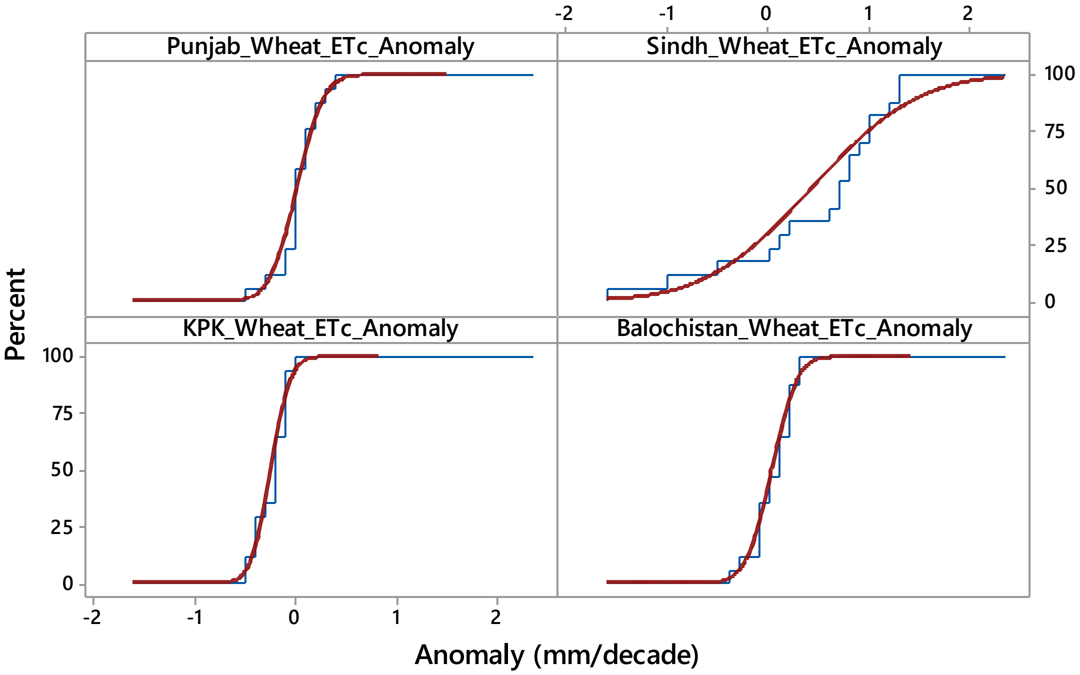


Figure 3.23 CDF base chart of ETc for the wheat season

Irrigation Requirement (IR):

The positive departure associated with IR anomalies for wheat season of Khyber Pakhtunkhwa , and Punjab for wheat season cover 65 and 75 percent of IR anomaly data as compared to the remaining two provinces. This means that in Khyber Pakhtunkhwa and Punjab IR will be low or less irrigation will be required in the Khyber Pakhtunkhwa and Punjab for the wheat season in the future. On the other hand, Sindh and Balochistan show an increase in the negative departure of IR anomaly for the wheat season and cover 70 and 80 percent of IR anomaly data on the negative side. This means that in Sindh and Balochistan IR will be high or more irrigation will be required in the Sindh and Balochistan for the wheat season in the future.

Now on the bases of shape parameters Balochistan and Punjab is more logarithmic and more exponential as compared to Sindh which means it will remain in the same division for larger values of percentage and it will be more persistent from zero to a larger value. On the other hand, Sindh and Khyber Pakhtunkhwa is less exponential and less logarithmic which means it will have more persistence from zero to larger value on both sides positive and negative of ER anomaly for the wheat season.

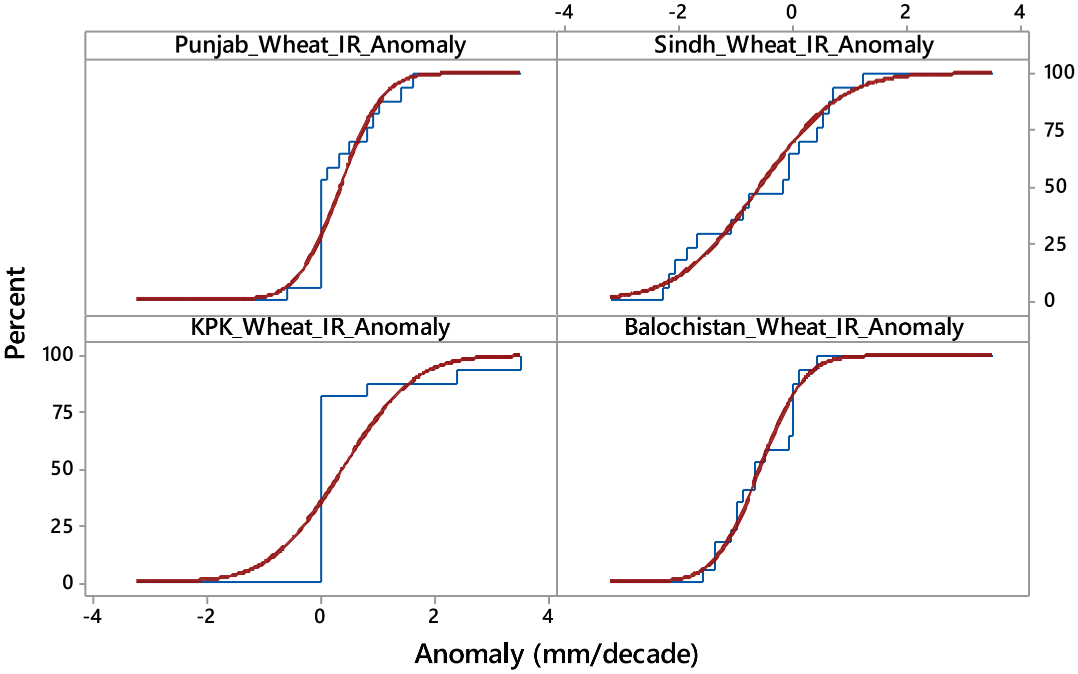


Figure 3.24 CDF base chart of IR for the wheat season

3.3 Inter-Seasonal Quantitative Analysis:

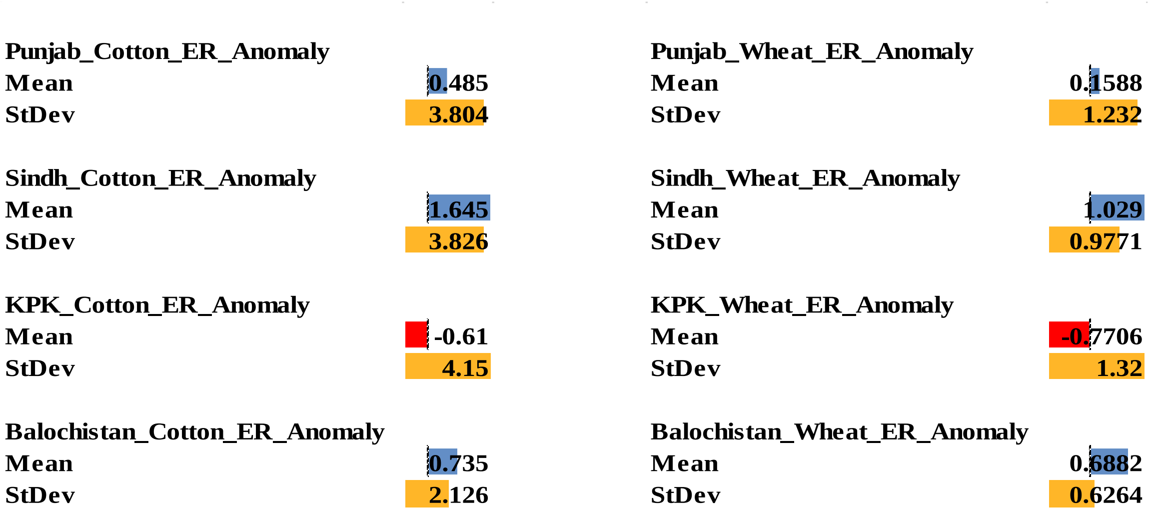
3.3.1 Effective Rain (ER):

The overall change in ER anomaly can be seen in the Sindh for the cotton season with a mean of 1.6 mm/Dm of positive change in the projection. The associated StDev anomaly is also high with a value of 3.8 mm/Dm which means that extreme value can potentially tend to push the mean towards a higher value of positive departure thereby increasing the mean of ER in Sindh for the cotton season. The mean of ER anomaly in Sindh for the wheat season is also high but relatively smaller than that of the cotton season with a value of 1 mm/Dm of change in the projection.

The associated StDev is intermediate at nearly 1 mm/Dm of an anomaly in the Sindh for the wheat season which means that higher positive departure is seen to be influenced by the extreme positive value in the projections.

The ER anomaly for Punjab and Balochistan regions show positive departure but with a value of mean less than 1 mm/Dm however, the associated StDev anomalies vary such that they remain higher for the cotton season as compared to the wheat season. On the other hand, the ER for both the cotton and wheat season in the Khyber Pakhtunkhwa shows negative departure which means that either slightly lesser or near to normal ER can be expected in the projection in the cotton and wheat season in the Khyber Pakhtunkhwa . Although the ER anomaly of the cotton season in the Khyber Pakhtunkhwa is slightly negative yet due to a larger StDev of 4.15 mm/Dm. The ER can potentially deviate from its mean in the projections.

Table 3.7 StDev and mean of ER anomalies.



Punjab_Cotton_ER_Anomaly		**Punjab_Wheat_ER_Anomaly**	
Mean	**0.485**	**Mean**	**0.1588**
StDev	**3.804**	**StDev**	**1.232**
Sindh_Cotton_ER_Anomaly		**Sindh_Wheat_ER_Anomaly**	
Mean	**1.645**	**Mean**	**1.029**
StDev	**3.826**	**StDev**	**0.9771**
KPK_Cotton_ER_Anomaly		**KPK_Wheat_ER_Anomaly**	
Mean	**-0.61**	**Mean**	**-0.7706**
StDev	**4.15**	**StDev**	**1.32**
Balochistan_Cotton_ER_Anomaly		**Balochistan_Wheat_ER_Anomaly**	
Mean	**0.735**	**Mean**	**0.6882**
StDev	**2.126**	**StDev**	**0.6264**

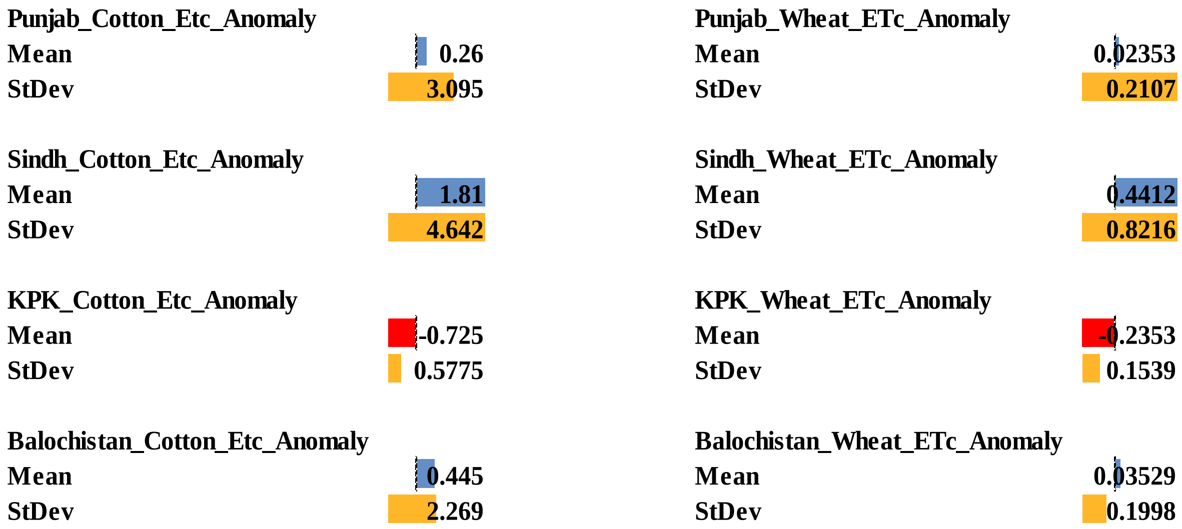
3.3.2 Crop Water Requirement (ETc):

The overall change in ETc is highest in Sindh for the cotton season with 1.8 mm/Dm of mean anomaly and with the StDev anomaly of 4.6 mm/Dm indicating a significantly high evapotranspiration rate in the projection. The ETc for the wheat season in Sindh is also positive with the small StDev which means that a smaller ETc with a smaller deviation is projected for the wheat season as compared to the cotton season in Sindh. The season highest StDev calculated for the ETc anomalies is seen in the cotton season for Punjab. However, its mean change is nearly close to normal. This implies that the slightly positive departure of the Punjab cotton anomaly is heavily influenced by the larger StDev of 3 mm/Dm which pushes the mean towards the positive side of the normal.

The ETc anomaly for the Balochistan wheat season does not very much in the future. However, for the cotton season, the Balochista shows more than 0.4 mm/Dm of mean change in its evapotranspiration rate with the StDev of 2 mm/Dm in the projection this means that cotton can be more affected than a wheat season in the future for Balochistan.

The Khyber Pakhtunkhwa displays the negative departure in both cotton and wheat seasons for ETc anomaly which means that their intermediate StDev pushes the mean evapotranspiration rate to negative thereby retaining more soil moisture in the projection.

Table 3.8 StDev and mean of ETc anomalies.



Punjab_Cotton_Etc_Anomaly		**Punjab_Wheat_ETc_Anomaly**	
Mean	**0.26**	**Mean**	**0.02353**
StDev	**3.095**	**StDev**	**0.2107**
Sindh_Cotton_Etc_Anomaly		**Sindh_Wheat_ETc_Anomaly**	
Mean	**1.81**	**Mean**	**0.4412**
StDev	**4.642**	**StDev**	**0.8216**
KPK_Cotton_Etc_Anomaly		**KPK_Wheat_ETc_Anomaly**	
Mean	**-0.725**	**Mean**	**-0.2353**
StDev	**0.5775**	**StDev**	**0.1539**
Balochistan_Cotton_Etc_Anomaly		**Balochistan_Wheat_ETc_Anomaly**	
Mean	**0.445**	**Mean**	**0.03529**
StDev	**2.269**	**StDev**	**0.1998**

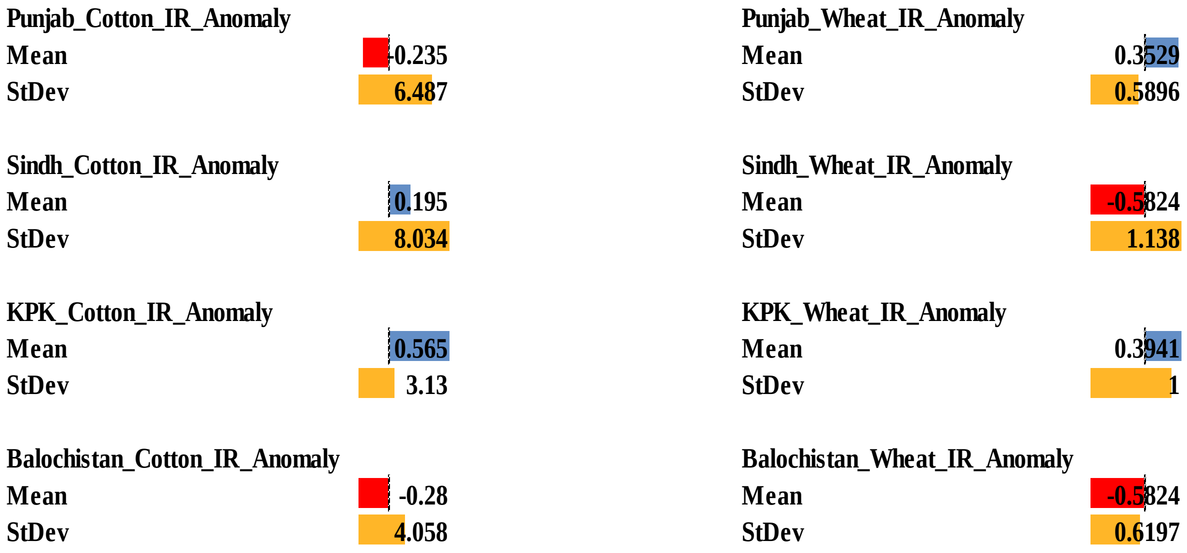
3.3.3 Irrigation Requirement (IR):

As per calculated data the mean change in the IR is seen to remain positive in the Punjab wheat (0.4 mm/Dm) Sindh cotton (0.2 mm/Dm) Khyber Pakhtunkhwa cotton (0.6 mm/Dm) and Khyber Pakhtunkhwa wheat (0.4 mm/Dm) in the projection. On the other hand, negative departure of IR is seen in Punjab cotton (-0.2 mm/Dm) Sindh wheat (-0.6 mm/Dm) Balochistan cotton (-0.3 mm/Dm) and Balochistan wheat (-0.6 mm/Dm) in the projections.

The StDev for cotton is overall higher than that for the wheat season in the IR anomaly. The overall highest deviation in the IR anomaly is seen for the Sindh season with more than 8 mm/Dm of StDev for the cotton season even with the small mean of a positive change in the IR of the cotton season in Sindh.

The associated impact will be higher due to high variability in the projection for the cotton season in Sindh. On the other hand, Punjab and Balochistan will tend to remain more secure in their soil moisture capacity due to negative departure in IR anomaly with significantly higher StDev anomaly for the cotton season in the projection.

Table 3.9 StDev and mean of IR anomalies.



Punjab_Cotton_IR_Anomaly		**Punjab_Wheat_IR_Anomaly**	
Mean	-0.235	**Mean**	0.3529
StDev	6.487	**StDev**	0.5896
Sindh_Cotton_IR_Anomaly		**Sindh_Wheat_IR_Anomaly**	
Mean	0.195	**Mean**	-0.5824
StDev	8.034	**StDev**	1.138
KPK_Cotton_IR_Anomaly		**KPK_Wheat_IR_Anomaly**	
Mean	0.565	**Mean**	0.3941
StDev	3.13	**StDev**	1
Balochistan_Cotton_IR_Anomaly		**Balochistan_Wheat_IR_Anomaly**	
Mean	-0.28	**Mean**	-0.5824
StDev	4.058	**StDev**	0.6197

3.4 Attribution and Discussion:

3.4.1 Cotton Season:

Although effective rain (ER) of Khyber Pakhtunkhwa mostly resides in the negative departure regime due to its negative median, yet the extreme whiskers of Khyber Pakhtunkhwa effective rain anomaly reach 10 which is higher among the other provinces this means that although the median rain contribution is negative, yet higher extreme forces the mean rain over Khyber Pakhtunkhwa to exhibit significantly positive anomaly in the projection.

Even with smaller effective rain (ER) in the future the crop water requirement (ETc) decreases which may be attributed to either stable or decreased temperature changes in the future over the Khyber Pakhtunkhwa region in fact lower temperature will contribute to the retention of soil moisture by restricting higher evapotranspiration rate in the future over the Khyber Pakhtunkhwa region.

For the crop water requirement (ETc) domain cotton season the Sindh and Khyber Pakhtunkhwa project a brighter picture in terms of their strongly negative medians. This pattern can be attributed to colder temperature anomalies in the Khyber Pakhtunkhwa and Sindh, which led to a smaller Evapotranspiration rate and hence crop water requirement (ETc) decreases.

Our claim is further strengthened by the projection of special distribution of near-surface relative humidity and precipitation anomaly which signals a significant increase in Khyber Pakhtunkhwa and Sindh .

Since the crop water requirement (ETc) of Sindh and Khyber Pakhtunkhwa for the cotton season is significantly negative than the other two provinces, The irrigation requirement (IR) also follows suit and tends to remain strongly negative in the medians declaring a lesser amount of irrigation requirement (IR) in the future.

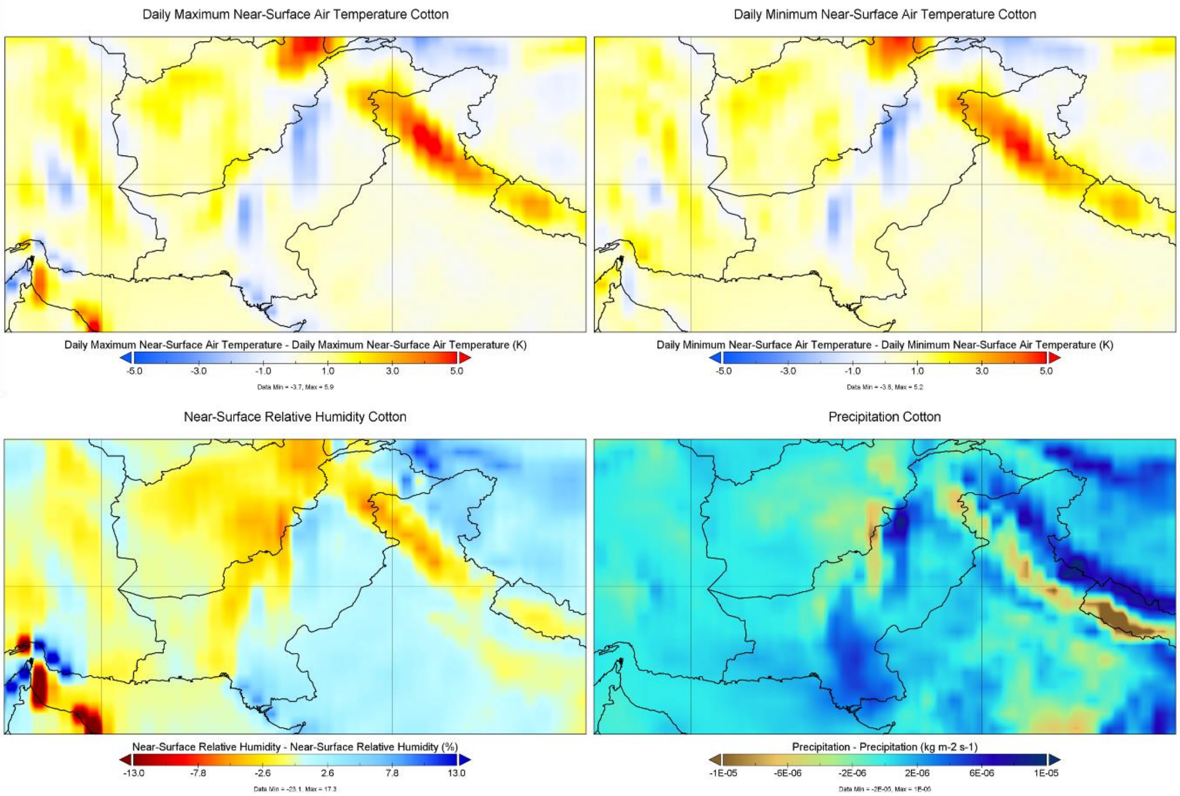


Figure 3.25 Map showing maximum and minimum air temperature, humidity and precipitation for the cotton season.

3.4.2 Wheat Season:

Although for the wheat season in Sindh, the ER frequency for positive departure increases with up to 4 occurrences of up to 3mm/Dm of surplus availability in the projections. The associated IR also decreases for the wheat season in Sindh with 4 occurrences of up to 2 mm/Dm of additional soil moisture availability in the projections. However, there are up to 6 occurrences of ETc anomaly for 1 mm/Dm seen in the anomalies for the wheat season of Sindh this indication is balanced by up to 4 occurrences of 1 mm/Dm IR anomaly for the wheat season in Sindh.

The highest crop water requirement (ETc) anomaly under the IQ Range analysis was seen in Sindh. It also has a median of 0.7 mm/Dm of increase which means that even without the inclusion of extreme values the overall ETc increases which pushes the IQ Range to nearly 1 mm/Dm in the projection of wheat season in Sindh. However, the IR is calculated to give a median of slightly negative departure but with a high IQ Range of 2.2 mm/Dm which may be attributed to a moderate increase of 0.8 mm/Dm in Effective Rain (ER) with the IQ Range of 1.7 mm/Dm in the projection of wheat season in Sindh.

The crop water requirement (ETc) anomaly for the wheat season in Sindh remains highly variable with a deficiency in soil moisture between stages 3 to 15 and slightly surplus soil moisture at the initial and final stages of crop development in Sindh. This deficiency gets offset by up to 2 mm/Dm of surplus water availability between stages 3 to 10 attributed to a reduction in IR between stages 6 to 12 by up to 2 mm/Dm for the wheat season in Sindh.

As seen through the analysis of Empirical CDF the crop water requirement (ETc) anomaly exhibit more than 70% of its departure in the positive zone for the wheat season in Sindh this causes the IR anomaly of the province to exhibit up to 30% of positive departure to full fill soil moisture capacity. The other 40% is replenished by the significant share of ER anomaly that goes to nearly 85% of the share in the positive departure for the wheat season in Sindh. Hence this surplus water can act to lessen the amount of Irrigation Requirement (IR) for the wheat season in Sindh in the projection.

Although the ER over Sindh in wheat season increases as shown in the figure yet due to the increase of up to 3^{o}c in minimum surface air temperature, the evapotranspiration (ET) rate becomes high and hence crop water requirement (ETc) increases however the surplus moisture available (more than 13%) over the province can subside the effect of additional crop water requirement (ETc) and hence can act to reduce the amount of IR in the wheat season in the projection.

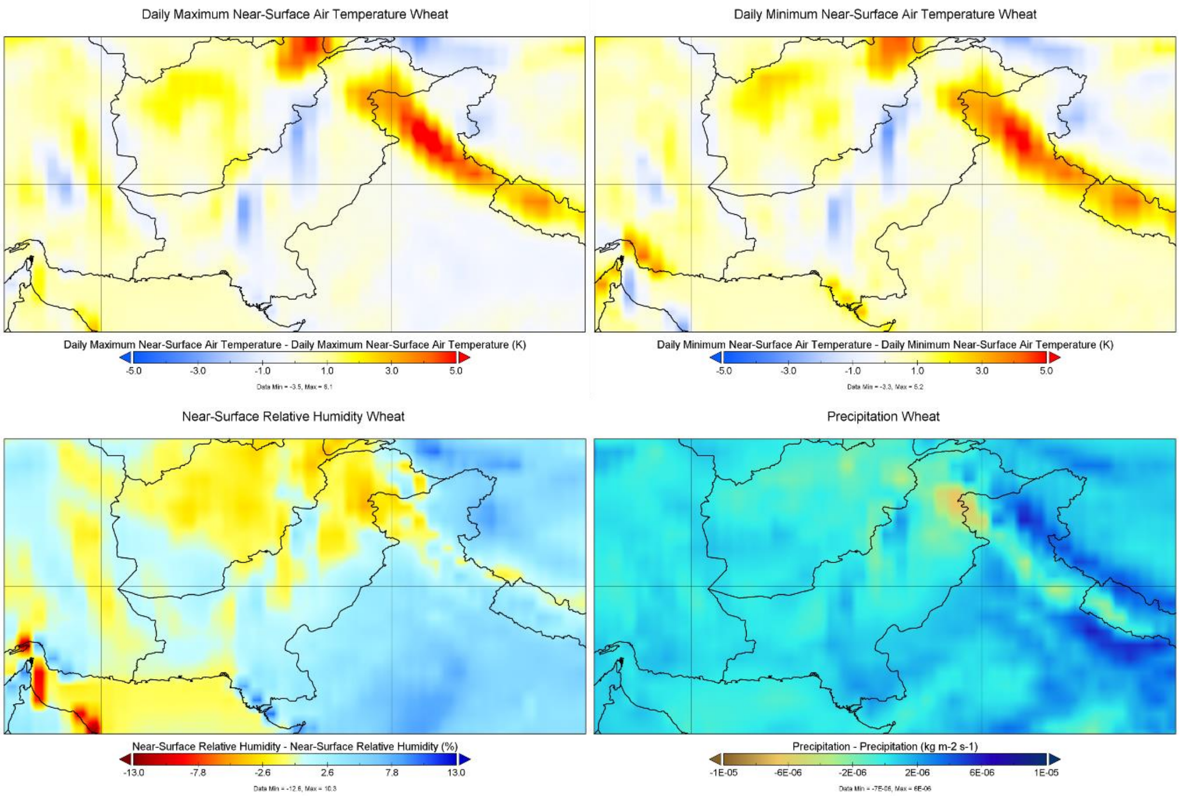


Figure 3.26 Map showing maximum and minimum air temperature, humidity and precipitation for the wheat season

4 CONCLUSION

The study focused on examining the projected impact of climate variability on the crop water requirement (ETc) in various provinces of Pakistan. To accomplish this, the researchers utilized DCPP data from the CMIP6 repositories available on the Earth System Grid Federation (ESGF) data link. This data was integrated into the CROPWAT model, which allowed for the evaluation of potential changes in effective rain (ER) anomalies, crop water requirement (ETc) anomalies, and irrigation requirement (IR) anomalies over a 10-year period in the future. Additionally, crop and soil data from existing literature were incorporated into the CROPWAT model to enhance the accuracy of the projected variations in these key variables.

The main findings of the study revealed variations in ER, ETc, and IR anomalies across different provinces of Pakistan during the cotton and wheat seasons. In the cotton season, Punjab exhibited a negatively skewed distribution for ER anomalies, indicating a higher frequency of positive departures. Sindh, on the other hand, displayed a positively skewed distribution for ER anomalies, with more frequency of negative departures. Khyber Pakhtunkhwa showed positive skewness in ER anomalies, with a higher frequency of negative departures, while Balochistan had negative skewness, indicating a higher frequency of positive departures.

During the wheat season, Punjab again showed a negatively skewed distribution for ER anomalies, indicating a higher frequency of positive departures. Sindh had negative skewness for both ER and ETc anomalies, with a higher frequency of positive departures. Khyber Pakhtunkhwa exhibited positive skewness in ER anomalies, with a higher frequency of negative departures, while Balochistan displayed positive skewness in ER anomalies, indicating a higher frequency of either normal or slightly negative departures.

Overall, the study highlighted the variations in ER, ETc, and IR anomalies across different provinces of Pakistan during the cotton and wheat seasons. These findings provide valuable insights for policymakers and agricultural stakeholders to understand the potential impact of climate variability on crop water requirements, aiding in the development of effective adaptation strategies. By incorporating climate projections and utilizing the

CROPWAT model, this study contributes to our understanding of the potential future changes in crop water requirements in Pakistan, helping inform decision-making and planning for sustainable agricultural practices.

5 RECOMMENDATIONS

For researcher

- In this thesis, DCPP data was used through CMIP6, which represents a 10-year duration projection. This short-term data is considered more reliable and authentic compared to long-term projections. However, the data used in the study is of intermediate resolution, providing information at the provincial level. For a more detailed analysis, such as examining cotton and wheat cropping systems at the district level, high-resolution data is required.
- In the thesis, the Cropwat 8.0 model was utilized for calculating crop water requirements (ETc). However, other integrated assessment models for crop water requirements, such as Aquacrop, could also be utilized and compared with CROPWAT 8.0.

For policy maker

- The study found that there are differences in the behavior of crop water requirements (ETc) during the cotton and wheat seasons in different provinces of Pakistan. Sindh and Balochistan exhibit higher scattering and more erratic behavior in ETc compared to Punjab and Khyber Pakhtunkhwa. Sindh shows significant variations and erratic behavior, while Punjab, Khyber Pakhtunkhwa, and Balochistan exhibit a more consistent pattern. Sindh also experiences the highest increase in ETc during the cotton season, while Khyber Pakhtunkhwa experiences a decrease in ETc anomalies for both seasons. These findings have implications for water management strategies in these regions.
- These findings provide valuable insights for policymakers and agricultural stakeholders to understand the potential impact of climate variability on crop water requirements, aiding in the development of effective adaptation strategies.

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7 APPENDICES

Appendix A: CROPWAT 8.0 Data Input Modules

7.1 Climate / ETo Module:

On the module bar to the left of the main CROPWAT panel, click the Climate/ETo symbol to choose this module. When you click the new toolbar button, a drop-down menu will appear, allowing you to rapidly choose a different data type from the one that will initially be displayed in the data window. You may specify the kind of new data and the data type to be input by using the new button in the File drop-down menu. In this module, the following data kinds are available:

- Month-to-month ETo Penman-Monteith
- Decade-to-decade ETo Penman-Monteith
- Daily ETo Penman-Monteith
- Month-to-month measured ETo
- decade-to-decade measured ETo
- Daily measured ETo

Monthly/Decade /Daily ETo Penman-Monteith:

The main purpose of the Climate/ETo module is data entry. It requires information on meteorological stations (country, name, altitude, latitude, and longitude), as well as climatic data that may be supplied on a monthly, decade-wide, or daily basis. CROPWAT just requires Temperature when it comes to climatic factors, however if available, Humidity, Wind speed, and Sunlight should also be included. Calculations and production are also included in this subject:

- Radiation
- Reference evapotranspiration (ETo) data using the FAO Penman-Monteith approach.

Monthly/Decade /Daily Measured ETo:

The Reference evapotranspiration information is needed by the Climate/ETo module (ETo). When ETo is supplied in this way, CROPWAT doesn't do any computations.

While the Climate/ETo module is activated, users may present data in a chart by choosing Chart from the toolbar.

7.1.1 Parameters:

I. Humidity:

With CROPWAT 8.0, air humidity can be expressed as real vapor pressure or relative humidity. The air's level of saturation is expressed as the ratio between the quantity of water that the surrounding environment contains and the most that it might store at the same temperature. Relative humidity varies with temperature, peaking around daybreak and troughing in the early afternoon. A percentage (%) is used to represent relative humidity. The 24-hour change in relative humidity for a fixed real vapor pressure is shown in the graph below.

II. Temperature:

According to agrometeorological standards, CROPWAT 8.0 denotes the air temperature measured at a height of 2 metres. Degrees Celsius (°C) are used to express temperature. CROPWAT 8.0 can operate with average temperatures in the absence of minimum and maximum temperatures. The daily maximum and daily minimum air temperatures are the highest and lowest air temperatures recorded during the course of a 24-hour period beginning at midnight. For calculating maximum and minimum temperatures across larger time frames, such as decades or months, the number of days in the period is divided by the total of the relevant daily values.

III. Sunshine Hours:

The length of clear skies during the day is symbolised by sunshine. It is influenced by the position of the sun and, as a result, by factors such as latitude and time of year, in addition to cloudiness. It can be quantified using the terms "sunshine hours," "daylight percentage," or "fraction of daylight" (fraction).

IV. Wind Speed:

CROPWAT 8.0 refers to wind speed as measured at 2 metres above ground, in accordance with agrometeorological norms.

Wind speed is displayed in CROPWAT 8.0 in kilometres per day (km/day) or metres per second (m/s).

CROPWAT evaluates the solar radiation reaching the soil surface based on available climate data.

V. Radiation:

Extra-terrestrial radiation (Ra) is the radiation received above the top of the earth's atmosphere on a horizontal surface, which varies based on latitude, date, and time of day. In CROPWAT calculations, solar radiation (Rs) measures the quantity of extra-terrestrial radiation reaching a horizontal plane on the soil surface, i.e., the fraction of extra-terrestrial radiation scattered, reflected, or absorbed by air gases, clouds, and dust. A portion of the solar radiation is reflected from the soil surface (? Rs), while the remainder is absorbed (Rns).

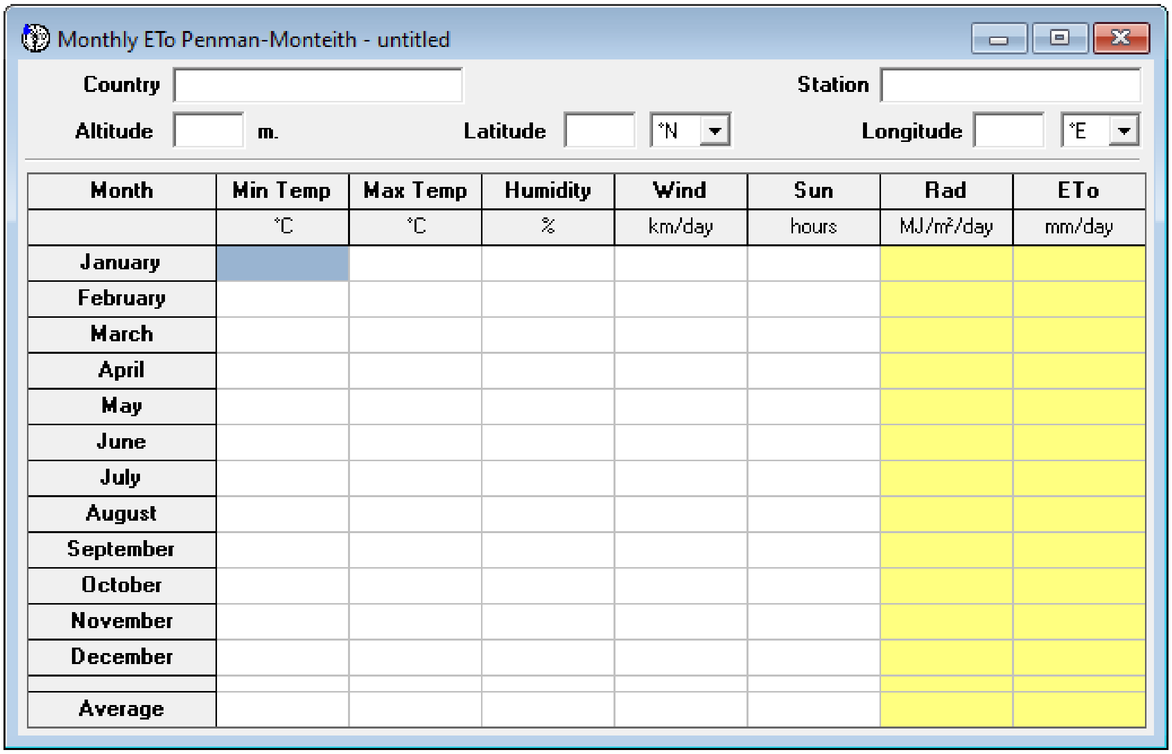
Radiation is measured in MJ /m2 /day.

VI. Reference Evapotranspiration (ETo):

The evapotranspiration rate from a Reference crop that is not water-stressed is referred to as the Reference evapotranspiration rate (ETo).

ETo was developed to investigate the evaporative demand of the atmosphere independent of crop type, crop development, and management approaches. Because water is abundant at the reference evapotranspiration surface, soil variables have little effect on ETo. The technique of relating evapotranspiration to a specific surface offers a reference to which evapotranspiration from different surfaces may be compared. It eliminates the need to specify a different evapotranspiration threshold for each crop and stage of development. Because they correspond to evapotranspiration from the same reference surface, ETo values measured or calculated in different places or seasons are similar.

The only variables influencing ETo are climate characteristics. As a result, ETo is a climatic metric that may be calculated using meteorological data. ETo expresses the evaporating power of the atmosphere at a certain place and time of year without taking crop characteristics or soil conditions into account. The FAO Penman-Monteith method is the only method recommended for determining ETo. This method was chosen because it produces values that are quite consistent with actual crop water usage data from around the world, as evidenced by many years of evaluations reported in the scientific literature. This method addresses the shortcomings of prior systems by directly incorporating both physiological and aerodynamic data. Furthermore, techniques for employing this method with restricted climatic data have been established.



Country

Station

Altitude m.

Latitude °N

Longitude °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m^2/day	mm/day
January							
February							
March							
April							
May							
June							
July							
August							
September							
October							
November							
December							
Average							

Figure 7.1 Parameters of climate module in CROPWAT 8.0

7.2 Rain Module:

The following data types are accessible in this module:

- Monthly
- Decades
- Daily

The Rain module is primarily for data input, requiring information on the precipitation values on a monthly, decades, or daily basis.

7.2.1 Parameter:

Effective Rainfall:

In terms of agricultural production, effective rainfall refers to the amount of precipitation that plants can utilise effectively. This indicates that some rain does not reach crops because of runoff (RO) and deep percolation (DP).

The type of soil, slope, crop canopy, storm intensity, and initial water content of the soil all affect how much water percolates into the soil. The most trustworthy method for calculating effective rainfall is field observation. Rainfall is quite effective when RO is little or non-existent. As very little volumes of water evaporate so quickly, light rains are ineffectual.

As a monthly rainfall input, the average, reliable, or genuine rainfall data can be given. Selecting adequate numbers for reliable rainfall should be done with caution and be based on different statistical assessments of historical rainfall records.

You may choose from a number of methods to measure effective rainfall by using CROPWAT 8.0's Rain Options.:

1. Fixed percentage of rainfall
2. Dependable Rain
3. Empirical formula
4. USDA Soil Conservation Service Method

Furthermore, it allows you to calculate irrigation without considering rainfall.

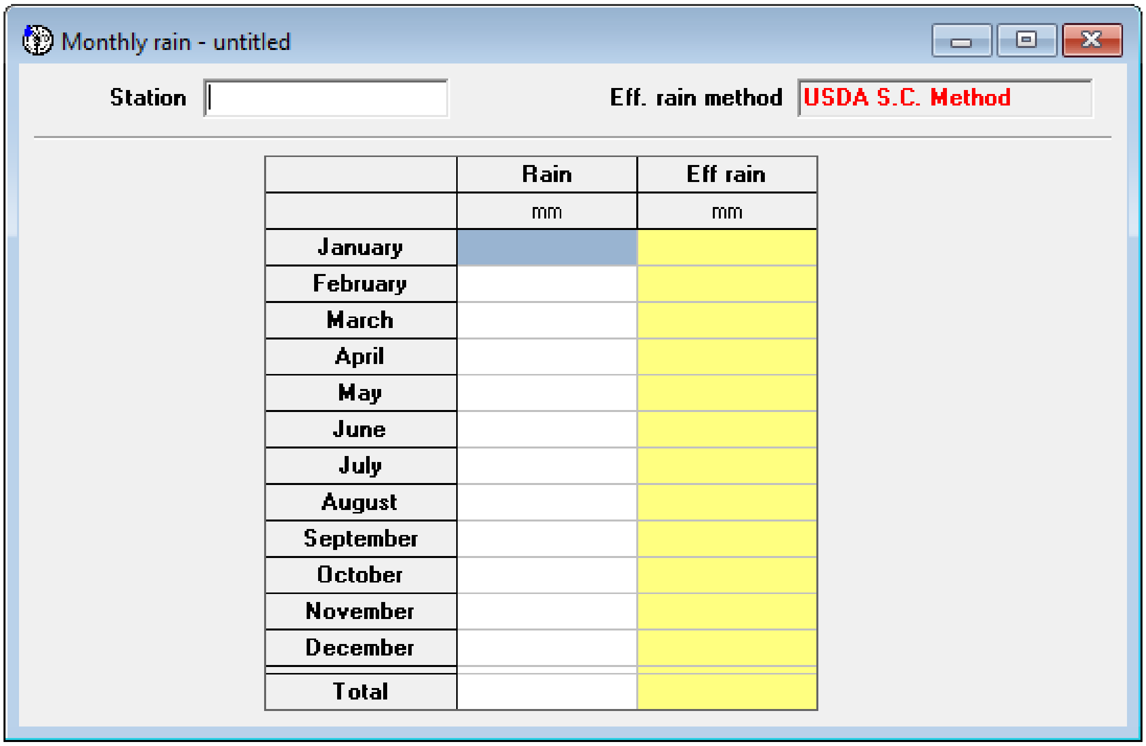
It should be noted that one of the techniques recommended in the Rain Options is used to compute the decades-effective rainfall, which is utilised in the CWR calculations.

Daily rainfall intake into the soil is calculated by scheduling, and rainfall losses from deep percolation and surface runoff are estimated using the actual soil moisture content in the root zone. Hence, the calculations for the water balance utilise total rainfall rather than effective rainfall. The growing season's daily accumulation of seasonal effective rainfall is shown in this module.

Effective rainfall has been determined using a method developed by the USDA's Soil Conservation Services (SCS).

$$P\ eff = \frac{[P\ total\ (125 - 0.6 \times P\ total)]}{125} \qquad \text{for } P\ total \leq (250 / 3)\ mm$$

$$P\ eff = (125 / 3) + 0.1 \times P\ total \qquad \text{for } P\ total > (250 / 3)\ mm$$



Station

Eff. rain method: USDA S.C. Method

	Rain	Eff rain
	mm	mm
January		
February		
March		
April		
May		
June		
July		
August		
September		
October		
November		
December		
Total		

Figure 7.2 Parameter of rain module in CROPWAT 8.0

7.3 Crop Module:

The Crop module is required for data entry and requires crop data at various phases of crop growth. Data must differ depending on whether the crop is non-rice or rice.

The Crop module is essentially data input, requiring the following compulsory parameters:

- Crop coefficient (Kc)

- Planting date
- Rooting depth
- Yield response factor (Ky)
- Stages
- Critical depletion fraction (p)

Maximum crop height should be specified if available.

The harvest date is computed automatically based on the planting date and the entire duration of the crop cycle depending on the length of the stages specified for another crop.

Crop data refers to the four phases of crop development:

- **The initial stage:** lasting till around 10% ground cover from the planting date.
- **The crop growth stage:** varies from 10% to full coverage when effective. During the beginning of blossoming, some crops receive complete, effective cover.
- **The mid-season period:** continues till the start of maturity after effective total cover. When crop evapotranspiration is reduced in comparison to reference evapotranspiration, this is often an indication that maturity is beginning. Other signs of maturity include leaf aging, yellowing, or senescence, leaf drop, or browning of fruit.
- **The late season period:** stretches from the start of ripening through harvest or full senescence. The crop is thought to have reached the end of its life cycle when it is harvested, dries naturally, reaches total senescence, or experiences leaf drop.

In most circumstances, crop parameter values for relevant stages allow for interpolation throughout the crop cycle's remaining phases.

As the four growth stages for seasonal crops and perennial crops do not always correspond, perennial crops call for a somewhat different approach. For CROPWAT 8.0 calculations, Kc can be measured continuously throughout the year in four phases of 90 days, or four phases can be detected throughout the growth season and a practical planting date can be determined.

7.3.1 Parameters:

I. Crop Coefficient (Kc):

The effect of elements that set one crop apart from another is taken into account by the crop coefficient (Kc). Using the crop coefficient approach, crop evapotranspiration under standard conditions (ETc) is calculated by multiplying reference evapotranspiration (ETo) by the relevant Kc.

Crop type and soil evaporation are the main determinants of KC, with climate and crop type playing a smaller role. Moreover, variations in ground cover, crop height, and leaf area cause the Kc for a certain crop to alter as it grows.

CROPWAT 8.0 requires Kc values at the start, mid-season, and harvest stages. Kc values are interpolated during the development and late-season stages.

- **Initial period**: the leaf area is small during this period, and evapotranspiration is mostly in the form of soil evaporation. As a result, the Kc is high during the early period when the soil is moist from irrigation or rainfall and low when the soil surface is dry.
- **Development stage:** as the crop grows and shadows more of the ground, evaporation becomes more limited, and transpiration progressively takes over as the primary activity.
- **Mid-season stage:** the Kc achieves its peak value at this point.
- **Late season stage**: By the conclusion of the late season stage, the Kc value reflects agricultural and water management methods. This score is high if the crop is watered often until it is harvested fresh. The Kc value will be low if the crop is allowed to senescence and dry out in the field before harvesting due to less effective stomata conductance of leaf surfaces

II. Yield Response Factor (Ky):

The Yield reaction factor (Ky), which connects relative yield decline to relative evapotranspiration deficit, assesses the yield response to water available. When comparing crop evapotranspiration under non-standard conditions (ETc adj) to crop evapotranspiration under standard conditions (ETc), a particular amount of water deficit may be present consistently throughout the crop's entire growth cycle or during any of the many development phases.

Generally speaking, the yield decrease with rising water deficit is smaller for crops like alfalfa, groundnut, safflower, and sugar beet (Ky 1), but it is greater (Ky >1) for crops like banana, maize, and sugarcane. When it comes to the various growth stages, the yield loss caused by a lack of water is often low during the vegetative and ripening stages and quite significant during the blooming and yield creation phases.

III. Critical Depletion Fraction (p):

The critical depletion fraction (p) indicates the key soil moisture level at which drought stress first manifests, affecting crop evapotranspiration and agricultural yield. Usually, between 0.4 and 0.6, values are given as a proportion of total available water (TAW), with lower values being used for delicate crops with small root systems in high evapo-rative situations and higher values being used for deep and densely rooted crops in low evapo-rative conditions. The evapotranspiration capacity of the atmosphere also has an impact on the percentage p.

IV. Stages:

The complete growing period for seasonal crops may be split into four separate development stages:

- **The initial stage (Init):** lasts from planting to around 10% ground cover. The length of this time varies greatly depending on the crop, crop variety, planting date, and environment.
- **Development stage (Deve):** This stage progresses from 10% ground cover to effective complete cover, which normally occurs as blooming begins. Effective cover can be defined as the moment when certain leaves of plants in neighboring rows begin to intermingle so that soil shading becomes virtually complete for row crops where rows often interlock leaves. In thickly seeded plants, such as grains and grasses, it

might be difficult to visualize the effective complete cover, hence the more clearly apparent stage of flowering is often utilised. Another indicator of effective full cover is when the Leaf Area Index (LAI, defined as the average total area of leaves per unit area of the ground surface) hits three.

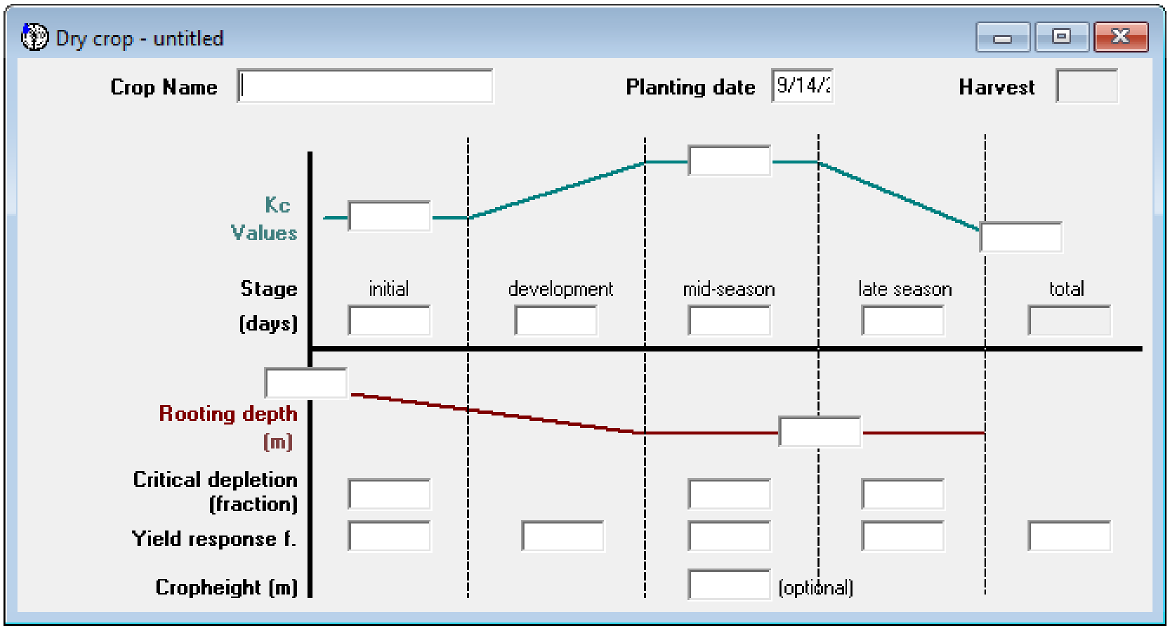
- **Mid-season stage (Mid):** This time extends from effective complete cover through the commencement of maturity, which is commonly characterised by the onset of aging, yellowing, or senescence of leaves, leaf drop, or fruit browning. For perennials and many annual crops, it is the longest stage, however, it can be quite short for vegetables taken fresh for their green greenery.
- **Late season stage (Late):** This time spans from the beginning of maturity until harvest or complete senescence.

The length of the development phases will be determined mostly by variety and growth circumstances, including temperature. As a result, values must be reviewed and changed for each site and growing season.

V. Rooting Depth:

The crop's capacity to use the soil water reserve depends on the rooting depth. Two values are necessary for the assessment of rooting depth during the growth season in CROPWAT 8.0:

- The seedling's first rooting depth, which is normally between 0.25 and 0.30 metres, represents the effective soil depth from which it draws its water.
- rooting depth at the start of midseason when it is fully developed. Vegetables have values between 0.5 and 1.0 m, whereas the majority of irrigated field crops have values between 1.0 and 1.40 m. At development, rooting depth is interpolated using a linear relationship with no input necessary.



Planting date 9/14/

Figure 7.3 Parameters of crop module in CROPWAT 8.0

7.4 Soil Module:

The Soil module is simply a data input module, and it requires the following parameters:

- Maximum infiltration rate
- Total Available Water (TAW)
- Initial soil moisture depletion
- Maximum rooting depth

This module also provides computations that provide the initial soil moisture.

7.4.1.1 Parameters:

I. Initially Available Soil Moisture:

It refers to the soil's moisture level at the beginning of the growing season. The sum of the initial soil moisture depletion and total available water (TAW) is expressed in millimetres per metre of soil depth.

II. Total Available Water (TAW):

The Total Available Water (TAW) indicator shows how much water is altogether accessible to the crop. Field Capacity (FC) and Wilting Point (WP) are defined as having different soil moisture contents (WP). As water cannot be kept beyond the FC level against gravity and instead naturally drains as deep percolation, there is no water available for the plants above the FC level. Conversely, because it is retained at high pressures inside the soil matrix below the WP level, water cannot be absorbed by plant roots.

The texture, structure, and level of organic matter in the soil all affect TAW. It is expressed as a millimetre for each metre of soil depth.

III. Initial Soil Moisture Depletion:

Initial soil moisture depletion refers to the dryness of the soil at the start of the growing season, that is, at sowing in the case of non-rice crops or at the commencement of land preparation in the case of rice. In terms of depletion from Field Capacity, the initial soil moisture depletion is stated as a percentage of Total Available Water (TAW) (FC). The default value of 0% corresponds to a fully wetted soil profile at FC, whereas 100% corresponds to the soil at Wilting Point (WP).

In most circumstances, the initial soil moisture condition may only be estimated, dependent on prior crop and fallow or dry season periods.

IV. Maximum Infiltration Rate:

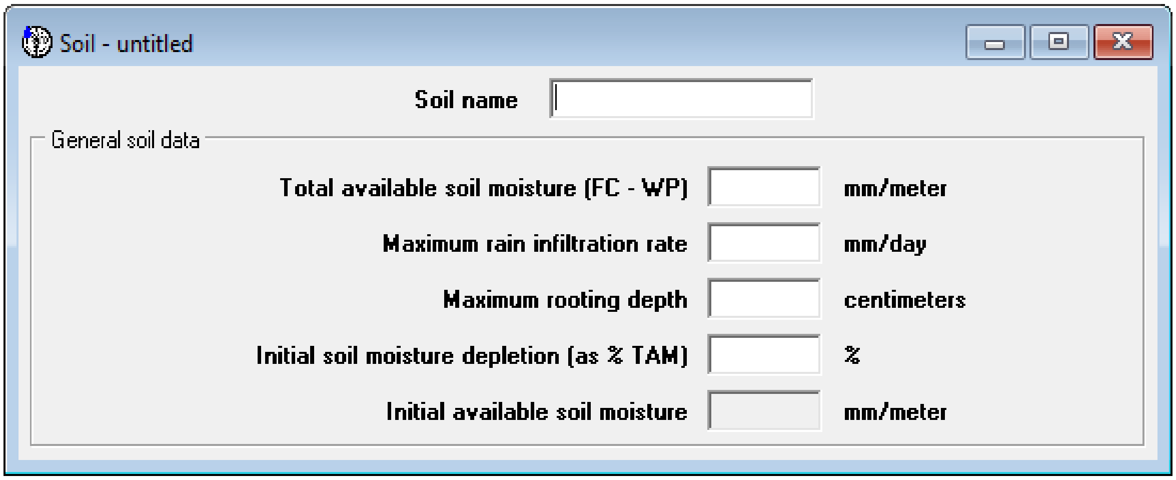
The maximum infiltration rate, stated in millimetres per day, reflects the depth of water that may enter the soil in 24 hours as a function of soil type, slope class, and rain or irrigation intensity. Under saturation, the maximum infiltration rate equals the soil's hydraulic conductivity.

The Maximum infiltration rate estimates runoff (RO), which occurs when rain intensity exceeds the soil's infiltration capacity.

V. Maximum Rooting Depth:

The maximum rooting depth can occasionally be limited by the soil and certain disturbed soil layers, even if the rooting depth is typically determined by the crop's genetic features. This is the case, for instance, when hardpans are present in locations where mechanised procedures have not been appropriately used. To prevent percolation losses and limit the depth of the crop's roots, a hardpan is purposefully created in rice fields.

The centimetre scale represents the maximum rooting depth. The default value of 900 cm denotes the absence of significant soil characteristics that can restrict root growth. Any value below the depth at which crops can root denotes a constraint on root growth.



Soil - untitled

Soil name

General soil data

Total available soil moisture (FC - WP) mm/meter

Maximum rain infiltration rate mm/day

Maximum rooting depth centimeters

Initial soil moisture depletion (as % TAM) %

Initial available soil moisture mm/meter

Figure 7.4 Parameters of soil module in CROPWAT 8.0

Appendix B: Climate Data for CROPWAT 8.0

Table 7.1 Climate hindcast data of Punjab

Months	Minimum temperature (tasmin)	Maximum temperature (tasmax)	Humidity	Wind Speed	Sunshine Hours
January	1.747311	17.27833	38.49781	75.14889	7.29
February	3.271167	19.35281	35.32474	78.92556	7.17
March	8.417156	25.33783	30.11916	78.98778	8.19
April	15.65456	33.19082	24.01902	77.58	9.22
May	19.63863	35.34349	31.9762	75.90778	10.28
June	24.45519	39.97507	29.00895	144.5367	8.97
July	25.90663	37.28393	50.60848	142.51	7.58
August	25.03046	35.11223	57.7303	136.2844	7.83
September	22.09842	34.4642	46.73266	98.77222	8.85
October	16.31662	31.75261	33.14222	43.82111	9.67
November	9.678433	25.40236	32.37116	44.78556	8.65
December	3.304244	18.68342	37.63317	79.30667	7.43

Table 7.2 Climate forecast data of Punjab

Months	Minimum temperature (tasmin)	Maximum temperature (tasmax)	Humidity	Wind Speed	Sunshine Hours
January	2.357078	17.70398	38.74926	81.85222	7.29
February	4.503678	20.8007	33.87354	69.31556	7.17
March	9.158244	27.0107	21.5219	80.02667	8.19
April	15.86596	32.37242	28.80333	64.62778	9.22
May	21.01093	36.9808	29.85903	76.27	10.28
June	25.03841	40.37184	31.27396	131.6389	8.97
July	27.09149	38.69141	46.27936	174.6044	7.58
August	25.15329	34.69874	61.0703	123.6267	7.83
September	22.14367	34.75307	47.52238	89.55444	8.85
October	17.56754	32.35568	34.00717	45.43889	9.67
November	9.531756	24.38736	38.39964	51.88667	8.65
December	3.814122	18.75647	40.10072	80.41444	7.43

Months	Minimum temperature (tasmin)	Maximum temperature	Humidity	Wind Speed	Sunshine Hours
January	6.674867	22.11037	28.8607	98.71731	9.09
February	8.108422	24.71724	25.10612	106.1329	8.51
March	13.07769	30.30391	23.67343	142.0223	9.58
April	19.24724	36.7244	25.29242	205.7828	9.56
May	22.34298	38.08738	36.64812	270.2737	10.48
June	24.91924	39.47799	46.19035	360.5954	9.33
July	26.19051	37.27112	57.03194	320.9446	7.89
August	25.73226	36.05288	59.41038	289.5539	8.37
September	23.38814	35.49643	53.72964	248.0803	9.49
October	19.58831	34.77	34.30535	98.11648	10.2
November	14.23007	29.67826	28.81678	59.90388	9.3
December	8.172478	23.34314	28.02139	122.0044	9.06

Table 7.3 Climate forecast data of Sindh

Months	Minimum temperature (tasmin)	Maximum temperature (tasmax)	Humidity	Wind Speed	Sunshine Hours
January	6.949078	21.79392	31.96551	130.33	9.09
February	8.973778	25.295	27.40731	100.3278	8.51
March	13.66593	31.26639	22.74921	168.1433	9.58
April	18.85852	35.8049	29.26128	221.3433	9.56
May	23.29278	39.29474	36.91192	330.9744	10.48
June	25.44218	40.5226	44.63507	379.2278	9.33
July	26.62573	37.81134	56.44677	369.1167	7.89
August	25.8077	35.47911	63.21835	264.3044	8.37
September	23.5776	35.66612	54.36536	217.45	9.49
October	20.54262	34.79959	37.80929	108.7222	10.2
November	13.89568	28.4595	31.04454	101.7544	9.3
December	8.680822	22.91582	32.67869	155.5244	9.06

Table 7.4 Climate hindcast data of Khyber Pakhtunkhwa

Months	Minimum temperature (tasmin)	Maximum temperature (tasmax)	Humidity	Wind Speed	Sunshine Hours
January	-8.7049	4.455122	28.8607	71.23444	6.52
February	-7.73802	5.4423	25.10612	72.23667	6.32
March	-2.87717	10.53916	23.67343	63.47111	6.48
April	3.683211	18.0774	25.29242	67.10889	7.71
May	7.794733	21.30697	36.64812	72.17778	9.9
June	12.89181	27.79609	46.19035	76.56667	9.98
July	16.59784	29.27822	57.03194	31.42111	9.13
August	16.4503	28.07684	59.41038	30.65667	8.77
September	12.27579	25.25808	53.72964	28.14667	8.58
October	5.847267	20.37899	34.30535	35.19556	8.87
November	-1.13768	12.74533	28.81678	52.31444	7.83
December	-7.33408	5.866111	28.02139	74.12444	6.15

Table 7.5 Climate forecast data of Khyber Pakhtunkhwa

Months	Minimum temperature (tasmin)	Maximum temperature	Humidity	Wind Speed	Sunshine Hours
January	-8.65182	4.956289	47.56435	66.00667	6.52
February	-6.78444	6.9759	47.85852	54.96222	6.32
March	-2.34006	11.94456	40.26548	53.56889	6.48
April	4.112067	17.64166	47.68521	56.37111	7.71
May	8.490256	22.54739	46.89415	73.88222	9.9
June	13.43194	28.05714	39.51436	65.11111	9.98
July	17.46544	30.72158	40.0134	25.75778	9.13
August	16.36766	27.97054	48.41874	21.03889	8.77
September	12.01546	25.59151	39.78188	23.29667	8.58
October	6.836233	20.93903	38.39482	27.76889	8.87
November	-1.36597	11.93483	47.67036	50.36333	7.83
December	-7.03936	6.382078	47.19527	67.69111	6.15

Table 7.6 Climate hindcast data of Balochistan

Months	Minimum temperature (tasmin)	Maximum temperature	Humidity	Wind Speed	Sunshine Hours
January	1.8224	15.94636	38.1645	81.51222	7.39
February	3.247811	18.24962	31.72801	108.9033	6.95
March	8.107656	24.01987	26.82717	145.4633	7.75
April	15.0385	31.09928	23.70859	173.2533	9.08
May	18.35102	33.34784	30.1488	172.9478	11.14
June	21.90419	37.72089	26.92108	169.0322	10.85
July	23.52681	37.89226	36.8341	132.6678	10.45
August	22.38034	36.64557	35.96797	125.4333	10.42
September	18.57203	33.73692	30.88473	128.3078	9.81
October	14.83274	30.3289	25.60511	88.26111	10.24
November	9.4941	24.33824	29.47706	65.15778	9.27
December	3.380978	17.56438	34.57203	74.24556	7.96

Table 7.7 Climate forecast data of Balochistan

Months	Minimum temperature (tasmin)	Maximum temperature	Humidity	Wind Speed	Sunshine Hours
January	2.0097	15.97239	38.87064	92.30778	7.39
February	3.783089	19.01856	32.55443	104.7467	6.95
March	8.975789	25.59871	22.78091	160.2511	7.75
April	14.78803	30.54859	26.3711	156.1867	9.08
May	19.47914	34.81246	27.57029	198.1233	11.14
June	22.74791	38.61171	25.72832	182.5389	10.85
July	24.20324	38.67248	35.6665	127.5678	10.45
August	22.6792	36.22924	39.74333	110.9378	10.42
September	19.1002	34.2074	31.33966	120.9667	9.81
October	15.34399	30.66341	26.8681	88.02333	10.24
November	8.816333	23.12853	33.17708	67.57889	9.27
December	3.321056	17.29518	37.30643	95.46111	7.96

Appendix C: Rainfall Data for CROPWAT 8.0

Table 7.8 Rainfall hindcast data of Punjab

Months	Rainfall
January	16.18091
February	22.21606
March	19.81015
April	17.00179
May	40.21329
June	16.2062
July	72.78341
August	73.68952
September	40.4344
October	15.56241
November	13.65207
December	13.65299

Table 7.9 Rainfall forecast data of Punjab

Months	Rainfall
January	15.30168
February	16.44553
March	13.84986
April	34.9387
May	28.74019
June	24.94611
July	54.81583
August	87.75041
September	39.95699
October	14.91344
November	19.01211
December	18.75726

Table 7.10 Rainfall hindcast data of Sindh

Months	Rainfall
January	2.783124
February	3.159388
March	0.647496
April	0.561908
May	5.532441
June	2.59024
July	29.1228
August	34.09213
September	18.88282
October	8.212671
November	1.431966
December	2.529586

Table 7.11 Rainfall forecast data of Sindh

Months	Rainfall
January	4.244173
February	2.736112
March	1.267427
April	3.774691
May	2.275967
June	2.453751
July	24.44548
August	68.7098
September	24.62872
October	16.01257
November	2.913393
December	8.426405

Table 7.12 Rainfall hindcast data of Khyber Pakhtunkhwa

Months	Rainfall
January	31.59111
February	42.04222
March	59.36444
April	57.49111
May	84.84444
June	29.89889
July	58.52111
August	59.06444
September	44.08778
October	28.55444
November	35.83333
December	27.54

Table 7.13 Rainfall forecast data of Khyber Pakhtunkhwa

Months	Rainfall
January	25.41333
February	39.22667
March	43.25667
April	79.70444
May	69.65889
June	38.86667
July	37.94444
August	61.51111
September	33.08667
October	27.53889
November	39.58
December	25.32889

Table 7.14 Rainfall hindcast data of Balochistan

Months	Rainfall
January	7.153333
February	8.342222
March	6.265556
April	4.796667
May	12.74222
June	2.956667
July	18.12
August	13.24556
September	7.85
October	2.958889
November	4.265556
December	10.01444

Table 7.15 Rainfall forecast data of Balochistan

Months	Rainfall
January	11.29
February	9.004444
March	5.026667
April	10.76889
May	8.667778
June	3.525556
July	14.63333
August	28.32667
September	8.287778
October	6.281111
November	8.253333
December	10.49333

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i EFFECT OF CLIMATE CHANGE ON CROP WATER REQUIREMENT USING CMIP6 DATA OVER PAKISTAN By HARAM RIAZ Department of Earth and Environmental Sciences BAHRIA UNIVERSITY, ISLAMABAD 2022 ii EFFECT OF CLIMATE CHANGE ON CROP WATER REQUIREMENT USING CMIP6 DATA OVER PAKISTAN HARAM RIAZ 01-262202-018 A thesis submitted in fulfillment of the requirements for the degree of MS in Environmental Sciences Department of Earth and Environmental Sciences BAHRIA UNIVERSITY, ISLAMABAD 2022 iii Dedicated To My beloved father & mother iv ACKNOWLEDGMENT I am very thankful to Almighty Allah, the most beneficial and merciful, and sympathetic who gave me the strength and power to do my best for this project. It is a great honor for me that supervise Dr. Humera Farah, senior associate professor at Bahria university, and co-supervisor Dr. Muhammad Tahir Khan, deputy director of the Pakistan Meteorological Department (PMD). I am thankful to them for their sympathetic attitude, guidance, moral support, cheering perspective, and valuable suggestions during the project. I also appreciate the cooperation of the Department of Environmental Sciences, Bahria University, Islamabad which makes it possible for me to complete the project. Most importantly, I would like to express my true appreciation to my family for their love, emotional support, understanding, and patience. I am thankful to my whole family, especially my affectionate mother, and my supportive father M Riaz, whose hands are always raising for my success. I also acknowledge my brother Khurram Riaz and his sister for their support, love, and cooperation. My friends for their guidance, support, love, and their prayers due to which I became able to complete my project. I also acknowledge Burhan Ahmad

Meteorologist at Pakistan Meteorological Department (PMD) for his valuable guidance and input. It is very honorable for me that I am post-graduating from Bahria University Islamabad where my great teachers polished my skills and encourage me in every aspect. May Allah Almighty give us the ability and strength to serve humanity and be kind to His creation. Haram Riaz v ABSTRACT In recent years, there has been an increased focus on studying the impact of climate change on crop water requirements, specifically evapotranspiration (ETc), due to the effects of temperature and precipitation variability. While many studies have projected long-term scenarios, there has been a lack of short-term predictions, particularly for a 10- year period, in the existing literature, specifically for assessing crop water requirement (ETc) in Pakistan. This thesis aims to address this gap by utilizing short-duration projected data from the Decadal Climate Prediction Project (DCPP) obtained from the Coupled Model Intercomparison Project Phase 6 (CMIP6) repositories. The objective is to assess the impact of climate change on crop water requirements across the provinces of Pakistan, focusing on the cotton and wheat seasons. To analyze ETc variations attributed to climate change, the study employed the CROPWAT 8.0 software, based on the guidelines provided by the Food and Agriculture Organization (FAO). Results revealed that IQ Range of ETc for the cotton season in Sindh and Balochistan exhibit higher scattering and more erratic behavior compared to Punjab and Khyber Pakhtunkhwa (KPK). The higher IQ Range values in Sindh (8.3 mm/Dm) and Balochistan (3.6 mm/Dm) contribute to this pattern, while Punjab and Khyber Pakhtunkhwa show a more consistent behavior with lower IQ Range values (1.65 mm/Dm and 0.9 mm/Dm) respectively.For the wheat season, the IQ Range analysis of ETc indicates that Sindh displays a higher scattering of anomaly data compared to Punjab, Khyber Pakhtunkhwa , and Balochistan. The higher IQ Range value in Sindh (0.9 mm/Dm) suggests significant variations and erratic behavior of ETc anomalies. In contrast, Punjab, Khyber Pakhtunkhwa , and Balochistan exhibit a more consistent pattern, with their ETc anomalies closer to the median values and lower IQ Range values (0.2 mm/Dm, 0.3 mm/Dm, and 0.3 mm/Dm) respectively, indicating a more stable ETc pattern. The study revealed significant findings regarding the projected changes in Crop Water Requirement (ETc) in different provinces of Pakistan during the cotton and wheat seasons. Sindh exhibited the highest increase in ETc during the cotton season, with a mean anomaly of 1.8 mm/Dm and a standard deviation (StDev) anomaly of 4.6 mm/Dm. Punjab displayed high variability in ETc anomalies during the cotton season, with the highest StDev observed. Balochistan showed an increase of more than 0.4 mm/Dm in evapotranspiration rate for the cotton season, with a StDev of 2 mm/Dm. In contrast, Khyber Pakhtunkhwa experienced a decrease in ETc anomalies for both seasons. These findings have significant implications for water management strategies in the respective regions. vi TABLE OF CONTENT CHAPTER 1 INTRODUCTION 1.1 Climate Change: 1.2 Climate Change Parameters: 1.2.1 Precipitation: 1.2.2 Temperature: 1.3 Crop Water Requirement as a Concept: 1.3.1 Major Factors Affecting Crop Water Requirement: 1.3.1.1 Climate Factor: 1.3.1.2 1.3.1.3 1.3.1.4 Impact of Crop Type on Crop Water Requirement: Influence of Soil Type on Crop Water Requirement: Influence of Water Table on Crop Water Requirement: 1.4 Literature Review on Crop Water Requirement: