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Research Article

Assessing the impact of climate-driven water stress on agriculture growth of Pakistan

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Abstract: This study was designed to investigate the role of changing climatic conditions on irrigation water security in Pakistan in order to quantify its implications for agricultural growth and, subsequently, the food security of the populace. Developing nations are highly vulnerable to climate crises, and Pakistan, in particular, is among the most vulnerable countries in this context. Over 60 percent of the population in Pakistan directly or indirectly depends on agriculture, which is extremely sensitive to the water stress triggered by escalating temperatures and unpredictable weather patterns. This study follows a quantitative approach, employing RStudio for mediation analysis where correlation, single-factor regression, and two-factor regression techniques were used to quantify the relation under study. The research findings revealed that the changing temperature and precipitation patterns have triggered an increase in water stress, negatively affecting agricultural growth to 13% from 1975 to 2019. This research is significant because it attempts to quantify the share of climatic changes in Pakistan's decreasing agricultural growth, elaborates on the country's current risks and mitigation potential, and puts forward policy recommendations to promote climate-resilient agricultural practices to facilitate adaptation to shifting climate regimes.

Keywords: Irrigation water, Water scarcity, Agricultural growth, Food security, Disaster risks, Climate resilience, Policy interventions, Mitigation policy, Adaptation policy.

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1. Introduction

Climate change is not just an environmental issue; it's a technology, water, food, energy, population issue. None of this happens in a vacuum (Titley, 2014). Climatic changes have a myriad of elements that affect natural ecosystems and human surroundings in various ways, for instance, climate variability and frequent extreme weather events affect biological systems and the water-food-energy nexus. The spatial heterogeneity of climate change effects is a widely studied subject and the current knowledge displays a rising trend in global temperatures with a considerable difference in temperatures between land and sea as well as between high and low latitudes. It also shows worldwide precipitation shifts with a projected rise in high-latitude rates and a decline in the rates of many tropical and subtropical land areas (Thornton et al., 2014). According to a report published by the World Bank Group (WBG), an estimated number of over 140 million economically vulnerable people from South Asia, Latin America, and Sub-Saharan Africa will have to relocate within the respective regions by 2050 because of climate-induced water shortages, decreased agricultural productivity, and the flood risk stemming from rising sea levels (Rigaud et al., 2018). These projections paint a bleak picture for the future of both humanity and the planet as the exacerbated weather events can have catastrophic consequences for human and natural systems.

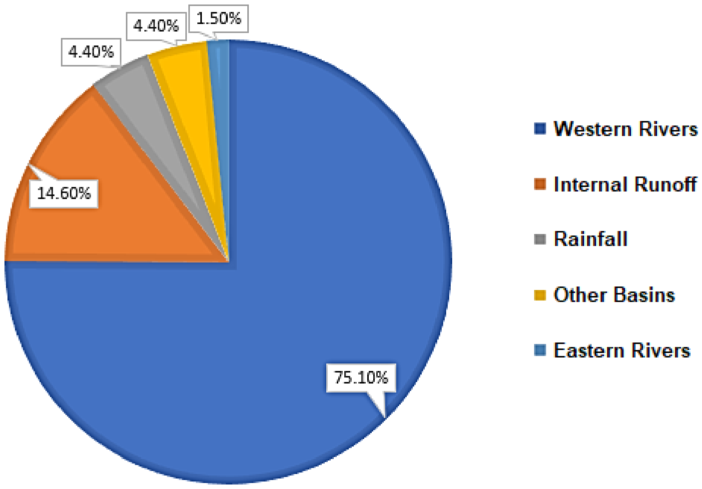
Climate change is a global concern and the evidence that climatic changes have picked up the pace is overwhelming. As documented by NOAA's National Centres for Environmental Information (NCEI), the average global temperature has elevated by 0.82°C as compared to the average temperature of the twentieth century. Moreover, the decade-wise temperature rise has accelerated, increasing by approximately 0.18°C since 1981, signifying a global trend of warming surface and ocean temperatures. Notably, 2016 and 2020 recorded temperatures 1.2°C higher than the nineteenth century mean, with 2021 ranking as the sixth-hottest year. The Asian region witnessed a temperature elevation of 0.17°C per decade from 1910 to 2021, doubling to 0.37°C in the longer term i.e., 1981-2021 (NOAA, 2021). South Asia, housing a quarter of the global population, is particularly vulnerable to climate change (Almazroui et al., 2020). The Intergovernmental Panel on Climate Change (IPCC) reports a 0.6°C increase in South Asia's average temperature from 2001–2010 compared to the 1950–2010 average, with a 0.9°C rise over the last century. Future projections suggest a further temperature increase ranging from 1.5°C to 4.5°C by 2050, intensifying climatic risks. Precipitation intensity has also risen by 4-8% since the 1950s, heightening the region's vulnerability to climate disruptions (Pachauri et al., 2014). Pakistan is ranked among the highly vulnerable countries of South Asia that are exposed to the intensifying threats of climatic crises. According to the Global Climate Risk Index by Germanwatch, Pakistan ranks 8th among the world's most climate-affected countries (Eckstein et al., 2021).

The average annual temperature of Pakistan has elevated by 0.57°C during the twentieth century. The rate of warming has also escalated, and the mean rate of elevation was recorded at 0.06°C per decade back in 2012. In northern Pakistan, the rise in temperature was 0.2°C above the long-term average of 0.6°C from 1901 to 2000. In addition, the precipitation frequency manifested a decreasing trend while the intensity was observed to increase almost all over Pakistan since 1965, and extreme weather happenings such as floods and droughts have become frequent as a consequence of unprecedented changes in the precipitation patterns, for instance, the back-to-back disastrous floods in the years 2010-11 and the super-cyclones of 2007 in the Arabian sea that hit the Makran Coast towards the south of Balochistan and Sindh

(Zhu et al., 2013). According to the "Climate Change Profile" published by Asian Development Bank (ADB), the frequency of yearly heatwaves has increased roughly five times over the last three decades and the sea level has ascended by approximately 10 centimetres along the shoreline of Karachi during the past century (Chaudhry, 2017). In addition, the recent floods of 2022 are a vivid example of the havoc wreaked by extreme weather events in Pakistan which affected more than 33 million people in the country (UNICEF, 2022), and inflicted damage to economic assets worth billions (ReliefWeb, 2022). However, despite the nationwide growing climatic stress, there is a severe lack of coping mechanisms in the state as the agenda to enhance resilience against climate crises has not yet been mainstreamed into the country's state, provincial, and sector-wise development policies, plans, and implementation processes (Afzal & Akhtar, 2021).

The main wellsprings of water in Pakistan include precipitation, river flows, stream waterways, glacial masses, and groundwater. The Indus basin is an uber source for Pakistan that meets the water demands of a huge portion of the country's population. It divides into five streams upon entering the region of Punjab province in Pakistan where the Indus River alone provides 65% of water while Chenab gives 19% and Jhelum gives 17% of the absolute waterway streams. Pakistan has an abundant amount of glacial masses than anywhere else on the inhabitable parts of the globe and a huge share of stream area in the Indus River system (IRS), yet the people in the country are on the verge of facing an intense shortage of water as the ground and surface water resources are progressively deteriorating. It can be attributed to the state's obsolete water conveyance framework which is a prominent factor in squandering the national water assets while little is stored in the repositories. Moreover, the precipitation frequency is decreasing due to shifting climate regimes and water added by precipitation is neither adequate nor customary to fulfil the expanding necessities of the incessantly growing population. The country receives approximately 70% of its annual precipitation in the long stretches of July to September, however, periods of pinnacle flow are observed during the rainstorm season from July to August. In addition, the snowmelt contributes a considerable share of water to Indus streams, ranging from 30 to 35% each, making it quite significant to the hydrological cycle of the country. However, climatic disruptions have influenced the pace of snowmelt and patterns of precipitation, elevating the risk of flooding and outrageous changes in the water cycle (Pathan & Pathan, 2021).

Figure 1: Percentage contribution of surface water resources in Pakistan



Source: Ahmed & Maira, 2021

The water availability in Pakistan has also been decreasing over the course of time while the water demand in the country is expected to rise under all climate change and consumption scenarios which is concerning as the resources are declining sharply. In 1950, Pakistan had its water availability standing at around 5,260 cubic meters per capita per year which has tumbled to about 1000 cubic meters per capita per year where this declining pattern is still progressing at alarming levels (Qureshi, 2020). In addition, the groundwater extraction rates have reached concerning levels, and at present, the total groundwater extraction stands at 65 billion cubic meters which surpasses the manageable cutoff points of 61 billion cubic meters recharge rate (Watto et al., 2021). There are around 10,000 public tubewells and more than 562,000 private ones that exploit the alluvial lands of Pakistan to a degree of nearly 38 million acre-feet out of the total capacity of around 50 million acre-feet. This water-scant status is further threatened by the pace of water use as Pakistan was ranked fourth-most noteworthy across the globe in the context of water consumption and first with respect to water power rate (i.e., water utilized per unit of GDP), presenting an impression of Pakistan as a more water-stressed economy than others in the South Asian region (Pathan & Pathan, 2021). As documented by the World Bank, renewable inland freshwater resources of Pakistan were 259 cubic meters per capita in 2018, representing a far lesser share of the total of 5,658 cubic meters of global freshwater resources as compared to the nation's demands (Li et al., 2022).

The agricultural sector is considered the backbone of Pakistan’s economy and at the time of partition, it was Pakistan’s only major economic asset. The agricultural sector still constitutes a huge part of Pakistan’s economy as it currently holds a 19.2% share of the country’s GDP. Moreover, 65-70% population is dependent on agricultural activities to sustain their livelihood, and nearly 38.5% labour force is associated with the agriculture sector (Pakistan Economic Survey 2020-21). Pakistan depends almost entirely on Indus and its tributaries for irrigation water as the Indus river plain, rated by NASA as one of the most over-stressed aquifers in the world, sustains the livelihood and survival of a large agricultural population of Pakistan (Buis & Wilson, 2015). Agricultural production, which is sustained by the Indus river irrigation system (IBIS), provides over 90% of the country’s food, making the water levels in Indus significant for the nation’s food security (Janjua et al., 2021). Pakistan has an extensive irrigation system, where around 60% area out of the total cultivable land of nearly 30 million hectares (Mha) is irrigated and around 16.85 million hectares of this cultivated area receives its water supply from the Indus River system solely. Therefore, a number of water engineering projects were undertaken during colonial and post-colonial times to set up the largest gravity-driven irrigation network on the Indus bowl streams (Hasan et al., 2021).

Pakistan’s irrigation system faces multiple challenges at both policy and operational levels, such as the average water storage capacity is 40% around the world whereas Pakistan’s capacity to store its average annual river flows stands far below the global average at only 10%. Moreover, Pakistan’s water resources are facing heavy stress due to conventional farming techniques like flood irrigation and the absence of hybrid seeds, poor water management mechanisms, and bad agricultural choices. The interprovincial rivalry over water allocations further aggravates the water management issues, including the lack of suitable systems to prevent excessive evaporation due to temperature rise, given that nearly 40% of water is lost this way, lack of mechanisms for irrigation subsidies and cost recovery, inequitable water distribution, and absence of basin-wise resource management structures. In addition, a huge portion of cultivable land (i.e., around 13%) suffers from salinity and almost 30% of agricultural land is rendered unfit for farming due to waterlogging. The recurrent storms also add to the severity of the situation, resulting in floods that inflict massive damage to crop areas. The shifting weather regimes exhibit area-wide variations in the country, and hence, need region-specific solutions; for instance, the coastal areas of Karachi require water drainage systems with higher efficiency as compared to inland areas (Salman, 2021). Furthermore, the glacial reserves of Hindu Kush-Karakoram-Himalaya (HKH) are known as one of the prominent water supply resources to the Indus river system in Pakistan and higher temperatures are adversely affecting these reserves, increasing the possibility of saltwater intrusion in the Indus delta (Ahmad, 2009).

The agricultural growth in Pakistan relies on the Indus waterways and the area irrigated by the Indus River system accounts for over 85% of the country's aggregate farming output. However, climate change is affecting the water security of the Indus system disproportionally as Pakistan's two major agrarian provinces, Punjab, and Sindh, are already facing challenges due to their limited water storage capacity. Around 20 to 25% of cultivable land in both provinces has incurred damages, putting this land at risk of becoming unfit for agricultural production. In addition, the temperatures of the region are expected to experience a four-degree Celsius increment while the precipitation intensity has been anticipated to increase by 3% by 2080s, posing a serious threat to agribusiness and costing up to 13% of the agrarian profitability (Mukhtar, 2021). At present, the agricultural sector faces the challenge to provide sufficient and healthy food that holds up to the criteria of nutritious needs and food preferences of the expanding population in addition to ensuring sustainable and secure supplies. According to a report jointly published in 2020 by five organizations of the United Nations (UN), namely the Food and Agriculture Organization (FAO), the International Fund for Agricultural Development (IFAD), the United Nations Children's Fund (UNICEF), the World Food Programme (WFP), and the World Health Organization (WHO), world's population is projected to increase and reach over 9.7 billion while the food demand across the globe is expected to shoot up by 70% reaching 2050s. The projection for Pakistan shows that the food demand in the country is expected to rise by 153% reaching 2050s (United Nations, 2020). To address the exceeding food demands in Pakistan, there is a dire need to take adaptive measures to save the country's agricultural sector from the catastrophic implications of climatic changes. Derived from secondary data sources, this research attempts to provide data-driven evidence of the severe implications of climatic changes on already inadequate and depleting water resources of the country and subsequently declining agricultural growth in order to propose a multipronged strategy to address the issue via policymaking.

1.1. Scope of study

Water is considered the single, most constraining driver of Pakistan's agricultural growth and productivity which can be attributed to the climatic zones of the country, ranging from arid to semi-arid regions. Pakistan is listed among the nations that have predominantly agriculture-dependent economies as this sector adds up about 20% to the economic growth; however, the state is encountering an acute shortage of irrigation water because the water demand has increased due to rising temperatures while the mean annual precipitation frequency in the country has reduced to around 240 mm and the groundwater availability has tumbled to an alarming level of around 1000 cubic meters per capita per annum. About 90% of agricultural land in Pakistan is heavily dependent on irrigation networks for cultivation, using the readily accessible river waterways, and this irrigation-fed cultivated area accounts for approximately 80% of the agricultural yield of the country. Most of the major crops in Pakistan are highly sensitive to climatic changes, namely rice, spices, cereals, vegetables, and other grains. By the virtue of elevated temperatures, shifting rainfall patterns, and the concomitant shortage of water, the water crisis not only regulates agricultural productivity at the individual level but also affects the agricultural sector at the system level. This study aims for a critical scientific inquiry into the impact of climatic changes on irrigation water security in the agriculture-dependent state of Pakistan.

1.2. Research questions

The research questions are What is the impact of increasing temperatures and unpredictable precipitation shifts on irrigation water security in Pakistan? How is the climate crises-induced stress on irrigation water wellsprings affecting the agricultural growth in the country? and What are the key areas the policymakers can target to minimize the implications of climate-driven water stress on agricultural growth?

1.3. Assumption

Increasing temperatures and shifting precipitation patterns are aggravating water stress and threatening the water security of the agricultural sector in Pakistan, resulting in decreased agricultural growth.

1.4. Significance of research

This study adds to social science inquiries, taking into account environmental sciences in the sense that it brings into light the implications of climatic changes on the ecological aspects of surface and groundwater shortages as wells as the effects of these changes on agricultural growth in Pakistan. Agriculture productivity is not only significant for the socioeconomic progress of the country's inhabitants but also for its contribution to the economic growth of the state; therefore, unveiling the real issues pertinent to agricultural growth is quite important from an applied perspective. This research is also significant because it attempts to quantify the impact of climatic changes on the agricultural growth of Pakistan by taking water stress as a mediator. Moreover, this study aims to bridge the gaps in the data on climate-induced crises in order to highlight the changing precipitation rates as well as heat-induced elevated evaporation and recession of glaciers, the phenomena which regulate the availability of water and subsequent agricultural production in Pakistan. Furthermore, this study elaborates on the possible policy interventions to facilitate adaptation to climatic changes via climate-smart agricultural practices and irrigation water management that can help improve the situation of food security, health, and survival of the people in the country.

2. Literature review

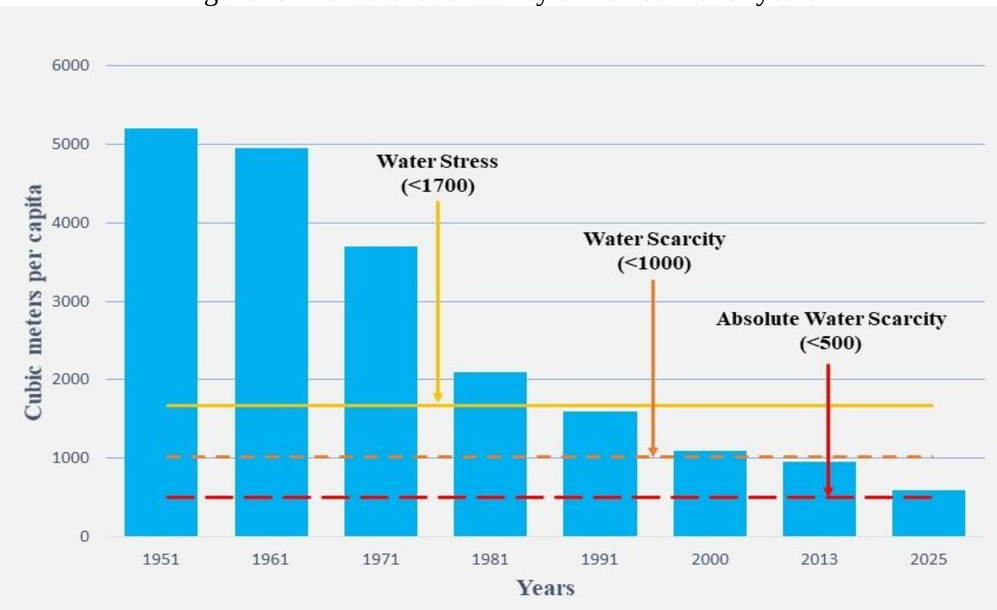
Climate change, in particular, has catastrophic effects on the water assets of the world as the snow and ice covers are decreasing, the sea level is climbing up, droughts and heat waves are more frequent and severe, and rainfall patterns and seasons are shifting due to increasing global warming (Solangi et al., 2022). Amid this chaos, groundwater reservoirs have become an exceedingly significant and strategic water resource to meet the demands of irrigation, households, and industry worldwide. Global estimates indicate an approximate annual extraction of 4,430 cubic kilometres of freshwater resources and 70% of this water is used for irrigation, 25% for industrial requirements, and only 5% for household needs. Global groundwater withdrawals constitute about one-sixth of the total freshwater withdrawals and can be estimated between 750 to 800 cubic kilometres per annum. Although the global share of groundwater used for irrigation is smaller as compared to surface water, it has multiple advantages over the volumetric access of surface water such as availability on demand, reliability, higher output, and lower capital investment (Qureshi et al., 2009). Therefore, freshwater security is listed among the key environmental crises of 21st century. According to scientists and governments around the world as future projections show that the global hydrological cycle will soon become unable to keep up with the world water demands.

United Nations Water (UN-Water) defined water security in an analytical brief titled “Water Security and the Global Water Agenda” as “the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability” (UN-Water, 2013). Similarly, in an executive summary published by Global Water Partnership (GWP) titled “Towards Water Security: Framework for Action”, water security is defined as a scenario where “every person has access to enough safe water at an affordable cost to lead a clean, healthy and productive life while ensuring the environment is protected and enhanced.” (GWP, 2000). As reflected by these definitions, water security is usually characterized by sustainable access to quality water in an area for drinking and other purposes that is sufficient for every individual. Therefore, water security is a key target in the United Nations’ list of Sustainable Development Goals (SDGs) and the “availability and sustainable management of water and sanitation for all” has been mentioned among SDGs as “Clean Water and Sanitation” (SDG-6). The importance of water is not limited to SDG-6, but it also runs through several other SDGs just as SDG-3 “Good Health and Well-being”, SDG-11 “Sustainable Cities and Communities”, SDG-12 “Responsible Consumption and Production”, SDG-13 “Climate Action”, SDG-14 “Life Below Water”, and SDG-15 “Life on Land” indirectly (United Nations, 2022).

Pakistan faces a predominant risk of aggravating climate disruptions, mainly due to its geography, where the rate of warming is higher that the global average. Moreover, the water assets of the country are highly sensitive to atmospheric shifts and climate change projections for Pakistan indicate further variations in the spatial and temporal distribution of water wellsprings in the state. The river networks of Pakistan receive their water supplies from the HKH glaciers which are receding rapidly as an outcome of global warming (Boone, 2008). Glaciers cover about 13,700 square kilometres of Pakistan’s area which makes up approximately 13% of the upper Indus Basin mountains and the glaciers of the HKH region are showing signs of shrinking and melting faster than any other part of the world (Butt & Iqbal, 2009). The rainfall patterns in Pakistan have also been changing abruptly, affecting agricultural productivity, water supplies, and forest resources. The drastic variations in the frequency and intensity of precipitation are evidenced by infrastructure and cropland damages caused by prolonged droughts and cataclysmic floods. The annual mean precipitation in 60% area of the country has declined to less than 250 mm, raising alarms for climate-smart farming and irrigation infrastructure, water-conserving irrigation channels, and efficient water storage and conveyance frameworks. Over 60% of Pakistan’s population depends on directly or indirectly precipitation-fed agriculture, therefore, weather patterns have a significant link with the growth of the agricultural sector. An estimated 23.4 Mha area in Pakistan is cultivated, of which only 18.36 Mha receives sufficient irrigation (Syed et al., 2022). As documented by the Consultative Group on International Agricultural Research (CGIAR), Pakistan was ranked as the 12th most detrimentally affected state in the context of agricultural vulnerability to climatic changes (Awan & Yaseen, 2017).

The water crisis in Pakistan is worsening as the country's might already have fallen below the threshold of 1000 cubic meters per capita per annum. Pakistan has a maximum 30-day water storage capacity and being a country with arid to semi-arid climate features, this limit is way below the recommended 1,000-day storage capacity (Parry & McCandless, 2017). The tumbling freshwater supplies in Pakistan have threatened the future of irrigation water security, mainly due to growing climate crises and insufficient storage capacities. Pakistan is ranked third among the largest global users of groundwater for irrigation. The surface water only facilitates the irrigation of 27% of cultivable land. Therefore, groundwater is extracted to irrigate the remaining 73% of the land, directly or indirectly. The province of Punjab alone utilizes over 90% of the total groundwater withdrawals (Qureshi, 2020). In addition, Pakistan's population has increased by five folds since 1960, adding to the water woes of the country, and according to future projections, more than 200 million inhabitants of the state are likely to face 'absolute water scarcity' by the year 2025 due to dwindling water supplies of 500 cubic meters per capita (Briscoe & Qamar, 2008). According to a recent survey, a service station in Pakistan alone consumes nearly 19,000 litres of water in one day and about 80 litres of that water is used to give a standard car one wash. In order to prevent this wastage, water recycling plants can be installed at the service stations as a single plant can help conserve about 60 to 70% of the water for reuse (Durrani & Marri, 2020).

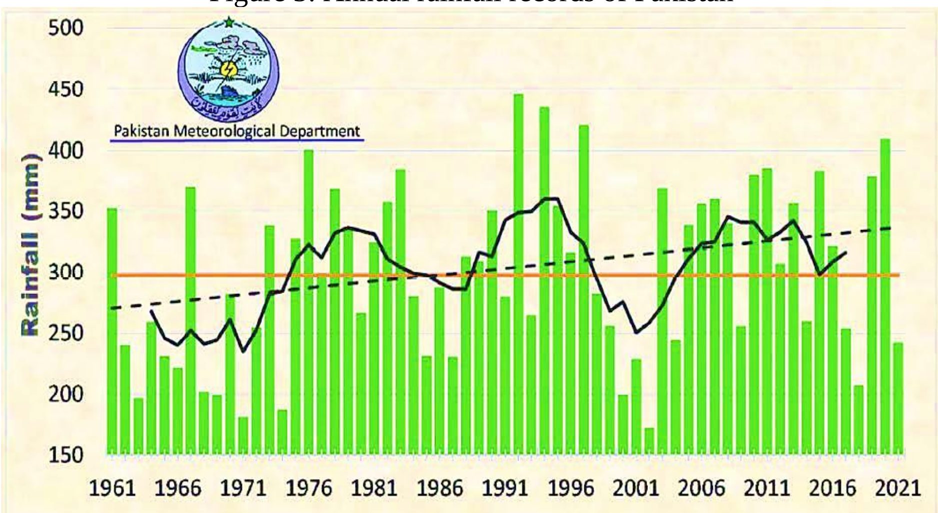
Figure 2: The water availability of Pakistan over years



Source: Briscoe & Qamar, 2008

There are not enough dams in the country to withstand the unpredictable shifts in weather regimes. In addition, water consumption patterns in Pakistan can be explained by the country's irrigation use efficiency as this sector represents a large portion of the economy. Nearly 70% of the country's population is directly or indirectly affiliated with farming activities, representing over 20% of Pakistan's national output, and the agricultural production is overwhelmed by four major crops with a high-water footprint: wheat, sugarcane, rice, and cotton. Over 90% of Pakistan's water is utilized for agriculture while the global normal for agricultural withdrawals is around 70% of total water usage and the credit goes to Pakistan's obsolete and inefficient water conveyance framework (Sleet, 2019). The overall irrigation network efficiency in Pakistan is nearly 40% as 88 BCM (billion cubic meters) of water out of 143 BCM goes to waste when employed through canals, distributaries, and watercourses (Qureshi & Ashraf, 2019). Moreover, the environmental changes have serious implications for both flood-prone and water-scarce regions as they aggravate the flood risk in monsoon and drought risk in dry seasons to alarming levels. A very noticeable decline in monsoon rainfall was recorded from 2010 to 2017 with typically heavy rainfalls in 2010 and an overall drier monsoon season in the past years (Safdar et al., 2019).

Figure 3: Annual rainfall records of Pakistan



Source: Pakistan Meteorological Department, 2021

High variability in monsoon rainfall makes it extremely difficult to plan crop sowing and harvesting and further increases Pakistan's reliance on Indus water for irrigation, however, the inefficient water consumption is the country's own fault. The total dam capacity of Pakistan is 27.81 cubic kilometres, which is far lesser than the country's needs. In addition, poor management of water resources leads to further loss of storable water as storage capacity cannot be utilized to its full potential due to lack of maintenance (Tariq & Van de Giesen, 2012). Moreover, Pakistan's poor agricultural practices play a significant role in aggravating water insecurity. For example, Pakistan's government not only allows but encourages the cultivation of highly water-intensive crops such as sugarcane. One kilogram of sugarcane takes roughly 1500-3000 litres of water to produce, yet it does not help in meeting the nutritional needs of the people of Pakistan. Neither does it contribute significantly to exports. Apart from growing water-intensive crops, water wastage due to poor irrigation and inefficient water consumption is a major driver of water and food insecurity in Pakistan. Furthermore, Pakistan does not allocate an adequate budget for wastewater treatment, desalination, and maintenance of artificial reservoirs (Sattar & Bhargava, 2019).

Discussion of climatic changes and their implications for the water assets of the country usually concentrates on the projected downturn in water flows of IRS and the expectedly higher rate of recession of HKH glaciers. These concerns are fairly understandable as glacial runoff generates around 50 to 80% of mean water flows in the Indus basin (Yu et al., 2013). However, the effect of climatic changes on soaring water demand cannot be overlooked due to the reliance of the agricultural sector on unprecedentedly shifting weather patterns which have augmented the evapotranspiration rates and reduced the soil moisture levels. Therefore, the immediate crisis Pakistan's water sector has to face due to climatic changes resides on the demand side as water demand is projected to increase under all consumption scenarios (Parry & McCandless, 2017). The agricultural sector is the backbone of Pakistan's economy and over 33% of value added in the agricultural sector can be attributed to the four major crops (wheat, rice, cotton, and sugarcane) in Pakistan while over 11% of the value is added by minor crops (Syed et al., 2022). Despite a noticeable population expansion, the production statistics of Pakistan's major crops indicate static growth over the past few decades, except for sugarcane, which highlights the growing concerns for national food security.

"Food security exists when all people, at all times, have physical and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life", as defined by the World Food Summit. There are four basic elements of food security, namely "availability, access, utilization, and stability" (FAO, 2003). The situation of global food security has improved since the 1990s as around 200 million people have been hauled out of hunger and a 26% decrease has been observed in the cases of chronic malnutrition in children (Hertel & Lobell, 2014). However, the situation in Pakistan is worsening due to aggravating effects of climatic changes. As indicated by the United Nations' Food and Agricultural Organization, over 26.3% of Pakistan's populace experienced severe food insecurity from the period of 2019 to 2021 (Li et al., 2022). In order to mitigate the impact of climatic changes on agricultural growth and food security, Pakistan needs to take immediate action to facilitate the process of adaptation to shifting weather regimes.

The term "adaptation" can be defined as the way of making changes in order to conform to the new usage, purpose, or circumstances (Dupuis & Biesbroek, 2013). In terms of the climate change phenomenon, the notion of adaptation can be defined in multiple ways as it has several components, such as vulnerability, exposure, sensitivity, and adaptive capacity (Brooks, 2003). But adaptation is usually referred to as a mechanism of altering the system of concern to attain a desirable setting. In this way, adaptation is seen as a concept different than resilience or sustainability as these two are "proxies" for the settings of a system (Hinkel, 2011). With the increasing policy activities to encourage adaptation to climate change across the globe, several academicians have started to compare the adaptation policies across the states at the national (EUROSAI-WGEA, 2012) and subnational levels (Craft & Howlett, 2013). The objective of these pioneer exploratory research was to highlight the challenges to implementing adaptation measures and refine the takeaways to understand climate change adaptation across different nationalities around the globe (Ford et al., 2011). Pakistan's government has done little to enhance its adaptive capacity and invest in climate-smart adaptation measures which are direly needed to ameliorate the agricultural growth conditions.

While the literature broadly acknowledges the catastrophic effects of climate change on global water resources, it lacks a focused exploration of the specific ecological consequences and cascading impacts on agriculture, particularly in the context of Pakistan. While the abovementioned studies touch upon the increasing demand for water resources and the looming water crisis in Pakistan, there is a need for a more detailed exploration of the specific factors, such as climate change, contributing to the impact of this water stress on the agricultural sector.

A more nuanced examination of the relationships between climate variables, water availability, and agricultural outcomes would enhance the understanding of these linkages. However, there is a lack of concrete and organized data on the intricacies of climate-induced water shortages in relevance with their implications for agricultural productivity in Pakistan, making evidence-based policies a far-fetched dream. Therefore, this study aims to fill the existing data gaps on implications of climate-induced crises. Emphasizing the significance of agriculture in Pakistan's socioeconomic fabric, this study provides a nuanced understanding of the challenges posed by climatic disruptions. The focus on water stress as a mediating factor and policy interventions for climate-smart agricultural practices, enhances this research's significance in offering practical recommendations and addressing the gaps in the current literature.

3. Research framework

The framework of this research reflects on the theories presented in the available literature, such as Döll (2002), Droogers (2004), Iglesias & Garrote (2015), Du et al. (2015), Ali et al. (2018), and Zhu et al. (2019) in order to develop a conceptual model for determining the course of research. The theoretical framework of this research is based on different studies exploring implications of changing climate regimes for irrigation water security and agriculture using different variables to quantify the degree of threat posed by climate disruptions. And the conceptual framework is embedded in the theoretical framework that uses data-based evidence to scrutinize the impact that climate-induced water stress has on agricultural sector growth and productivity in Pakistan.

Döll (2002) studied the impact of climate variability on changing irrigation requirements across the globe, asserting that anthropogenic climatic changes impact water availability and exacerbate demand as specific zones become drier and warmer. Döll chose to study irrigation as this water-use sector is highly sensitive to changing weather patterns, and for this purpose, Döll employed the global model of irrigation requirements (GIM) developed by Döll & Siebert (2001). This model utilized climate inputs, including temperature, precipitation, and potential evapotranspiration, to evaluate irrigation water demands in relation to cropping patterns. The study considered irrigation water usage efficiency, denoted as the ratio of net irrigation demand to total irrigation withdrawals. The findings indicated a noticeable increase in long-term mean irrigation water demand by the 2020s and 2070s under changing climatic patterns.

Drooger (2004) examined climate change adaptation in Sri Lanka, seeking to provide guidelines for enhancing food security and preserving environmental quality. Climate change was assessed using long-run temperature and precipitation averages, exploring its impact on irrigation requirements and food productivity. Two models were utilized: SWAP (Soil-Water-Atmosphere-Plant), a physical field-scale model developed by van Dam et al. (1997) and WSBM (water and salinity basin model) i.e., a basin-scale water allocation model developed by Droogers et al. (2001). These models aimed to analyse climate-induced challenges to water resources and food security in the Walawe basin. The findings revealed significant challenges in the Walawe basin due to rising temperatures and declining precipitation frequencies, resulting in increased irrigation requirements and decreased crop yield.

Iglesias & Garrote (2015) presented a case study of Europe to explicate the management of agricultural water in the region and highlight optimal strategies for climate adaptation. This research took into account the findings of more than 165 publications on the subject for explaining the significance of irrigation water handling in the context of reducing water availability, erratic precipitation changes, and frequent extreme weather events: linking it all to food production in the region. The findings revealed that the precipitation in some areas is expected to increase, bringing localized benefits. However, the overall water availability in the region shows a declining trend due to rising temperatures, resulting in increased irrigation requirements, agricultural land-use changes, and deteriorating water and soil quality.

Du et al. (2015) studied food security in China through the lens of water-resource strategies in agriculture. This research took the stance that without efficient irrigation water use, it would be impossible to ensure food security of the expanding population. This study employed the variables of "irrigation water-use efficiency" and "water productivity" to explain agricultural output, intending to encourage deficit irrigation and water resource conservation amid globally changing climate regimes. The findings of this research revealed that allotment of water resources, efficiency of irrigation water usage, and capacity to mitigate the impact of extreme weather events are highly significant for sustainable agricultural productivity, and subsequently, the food security of the population in the region.

Zhu et al. (2019) focused on rainfall patterns and irrigation networks to study the annual average water security in China and assess its linkage to the food production in the country. This research proposed a framework to analyse the irrigation water security in which the water stress index was calculated as the deficit between water supply in the region and aggregate water demand for irrigation. They referred to the data for the time period of 1961 to 2015 to explore the case of 23 core field crops in China. The aggregate water demand was computed based on FAO-recommended coefficients and evapotranspiration rates for the selected crops. The water availability for rain-fed agriculture was computed using precipitation data and for irrigated agriculture was calculated based on irrigation water withdrawals.

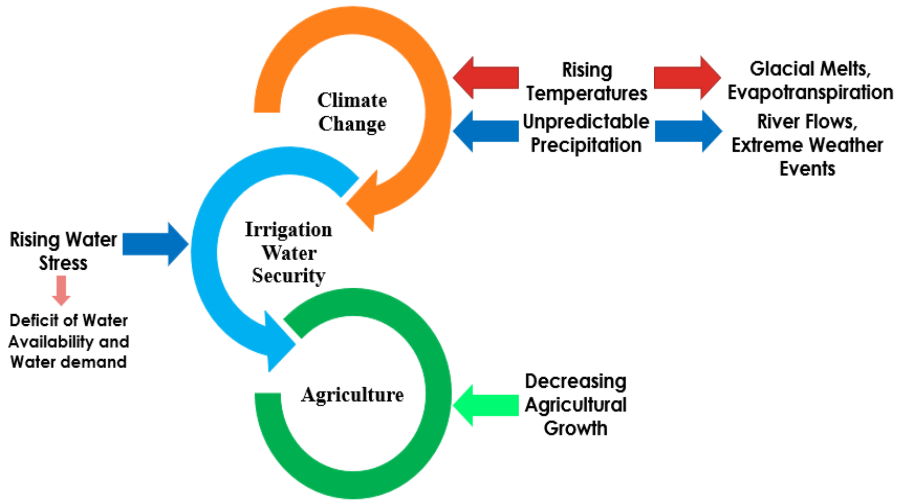
Ahmed et al. (2016) selected the region of Pakistan in order to highlight the water-related implications of changing climate patterns for both agricultural resources and public health. This study explained climatic changes in terms of rainfall, temperature, and humidity. It spelled out the impact of changing climatic conditions on the water assets in terms of water availability, water quality, and recurrent floods and storms, connecting these to the agricultural growth of the country and the prevalence of waterborne diseases in the populace. The findings revealed that climate-induced degradation of water availability adversely affects agricultural production and livestock. The study also uncovered that deteriorating water quality and increased humidity contribute to the spread of water-borne diseases such as cholera and vector-borne diseases like malaria and dengue fever.

Ali et al. (2018) also presented the case of Pakistan to underscore the significance of irrigation water management in relation to food insecurity and poverty prevalence. The research involved an extensive field survey of 950 farmers nationwide, collecting data to assess water-management strategies and their implications for food security and poverty prevalence. The study disclosed that escalating temperature and precipitation changes have led to an increased demand for water, while water availability has decreased to alarming levels. On the other hand, Ali et al. (2021) employed empirical-theoretical methods to evaluate the impact of climatic shifts on Pakistan's agricultural sector. This research utilized data on annual mean air temperatures and precipitation rates, employing a two-factor regression model to analyze the influence on agricultural productivity. The findings indicated that both climate variables negatively affected agricultural production in the country. All these studies serve as theoretical references, forming the basis for this research's conceptual framework. They aided in defining the dependent, independent, and mediating variables for analysis and informed the selection of measures to compute the variables under study.

4. Conceptual framework

The conceptual framework of this study revolves around a comprehensive analysis of the factors which relate to climate-induced water scarcity in the state of Pakistan and the extent to which this relationship affects the agricultural sector of the state. To compute the independent variable, climate change, the measures of annual mean temperature and precipitation were selected. The mediating variable, irrigation water security, was characterized by water stress percentage which is measured as the deficit between water availability and demand. To calculate the dependent variable, the effect on the agricultural sector, the measure of agricultural growth was selected. In Pakistan, there is very limited research on this subject, and the lack of concrete and organized data has made evidence-based policies a far-fetched dream. Moreover, the role of governance and policy in managing climate-driven irrigation water risks to agriculture has not been addressed properly in the available literature.

Figure 4: Conceptual framework of research



5. Research methodology

This study has an explanatory nature, and it follows the cause-and-effect model to quantify the degree to which climatic disruptions are adding to the irrigation water security of Pakistan in order to generate evidence on the exact contribution of climate-induced water stress in the reduction of the agricultural growth rate of the country. The time period of 1975 to 2019 was selected for the analysis of trends as it accounts for over 45 years and the reason behind choosing this timeframe was that the drastic changes in climate and water resources of Pakistan have become more explicitly visible during this time period. This study employs quantitative research model to present the analysis of the role of changing climatic conditions in irrigation water insecurity and the resulting implications for the agricultural sector. Data for analysis of the subject under study was obtained from secondary data sources such as institutional reports and relevant publications. Secondary data resources can be defined as the platforms where the required information has already been collected by conducting the research in different times and spaces and using certain models that employ different variables. Generally, official personal records, publications, reports, previous studies, and mass media commentaries published by the government, semi-government, or international institutions are referred to as secondary data sources. Therefore, the relevant documents were retrieved from the online archives of state authorities and international organizations that have expertise in climate change, water security, and agricultural research were collected.

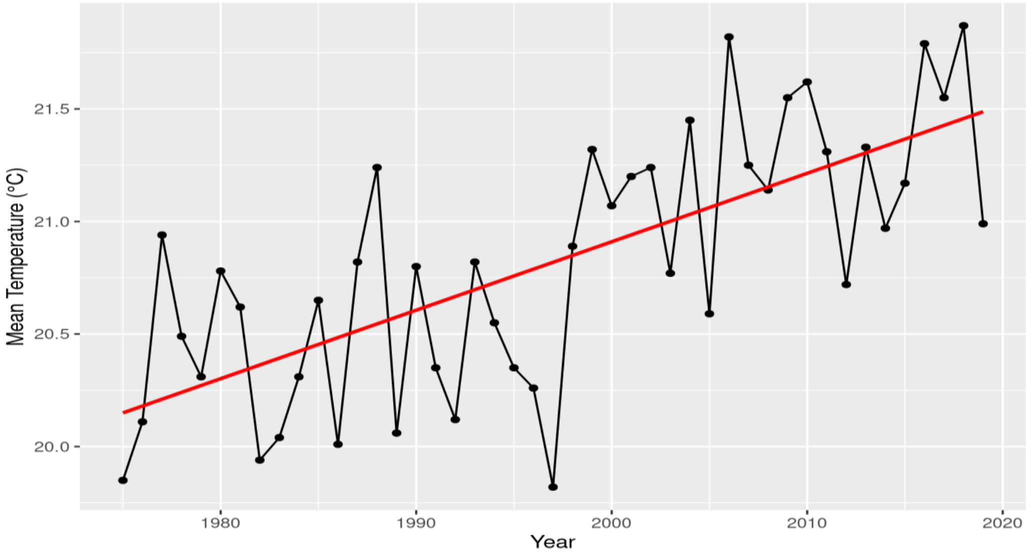
For quantitative analysis, time-series data for the time period of 1975 to 2019 (over 45 years) was collected from reliable sources to compute different variables. The data for the climate change variables was collected from the "Climate Change Knowledge Portal" by the World Bank Group. The source provided information on the measures of annual mean precipitation and annual minimum, maximum, and mean temperatures for Pakistan (World Bank, 2022). The data for Pakistan's population was collected from Worldometer which is "run by an international team of developers, researchers, and volunteers with the goal of making world statistics available in a thought-provoking and time-relevant format to a wide audience around the world" and it has been ranked as one of best websites by the American Library Association (Worldometer, 2022). The data for the annual per capita water availability in Pakistan, freshwater withdrawals, agricultural water withdrawals, and water stress was collected from the AQUASTAT, which a platform creates by FAO to provide information on water resources and agricultural water management (FAO, 2022). The data for the agricultural growth of the country was collected from the Economic Surveys of Pakistan. Lastly, the data for the value added to Pakistan's GDP by the agricultural sector and the prevalence of moderate to severe and severe food security in Pakistan was collected from the Database of "World Development Indicators" created by the World Bank. This database retrieved the data for food security from FAO and the data for the value added by the agricultural sector from national accounts of the World Bank and OECD (World Bank, 2022).

RStudio was employed for the quantitative analysis; it is an integrated development environment for R (a programming language used for statistical computations and graphic visualization). The correlational analysis was performed to explain the strength and nature of the relationship between different variables of the study. In addition, a regression model was developed to quantify the degree of impact climatic changes inserts on the irrigation water security of Pakistan and how this relationship affects the agricultural sector. For this purpose, mediation analysis was performed to get a holistic view of systemic linkages between the variables under study. The measures of average yearly temperatures and precipitation were used for climate change, the irrigation water security was defined in the context of the deficit between water availability and demand, and the impact on agriculture was computed in terms of agricultural growth in the country.

6. Results and discussion

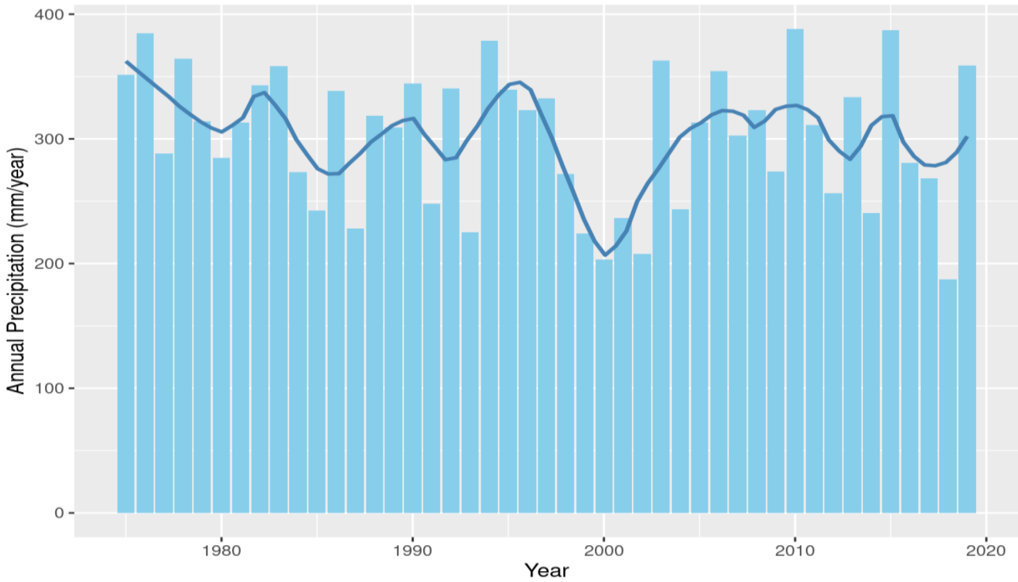
This study used quantitative research approach to address the research questions pertaining to the subject under study. The theoretical framework provides the foundation for the variables under study, providing insights to inform and shape the quantitative analysis. The overall findings of the study revealed that the variations in temperature and precipitation have triggered an increase in the water stress of Pakistan, in turn negatively affecting the agricultural growth in the country.

Figure 5: The rise in annual mean temperature of Pakistan from 1975 to 2019



The timeframe of the study was selected from 1975 to 2019, making up over 45 years, and the limits of the timeframe were defined on the basis of data availability. The quantitative section of this research computed the implications of climatic changes for the security of irrigation water and the role of this climate-driven water stress in the agricultural sector's growth. RStudio was employed for data visualization, correlational analysis, and regression analysis. The independent variable i.e., climate change was defined by two measures: annual mean temperature and average annual precipitation rates of Pakistan. The trends for annual mean temperature in the country displayed an increase of over 1.3°C from 1975 to 2019 where both the minimum and maximum temperatures have been observed to rise gradually in the second half of the timeframe.

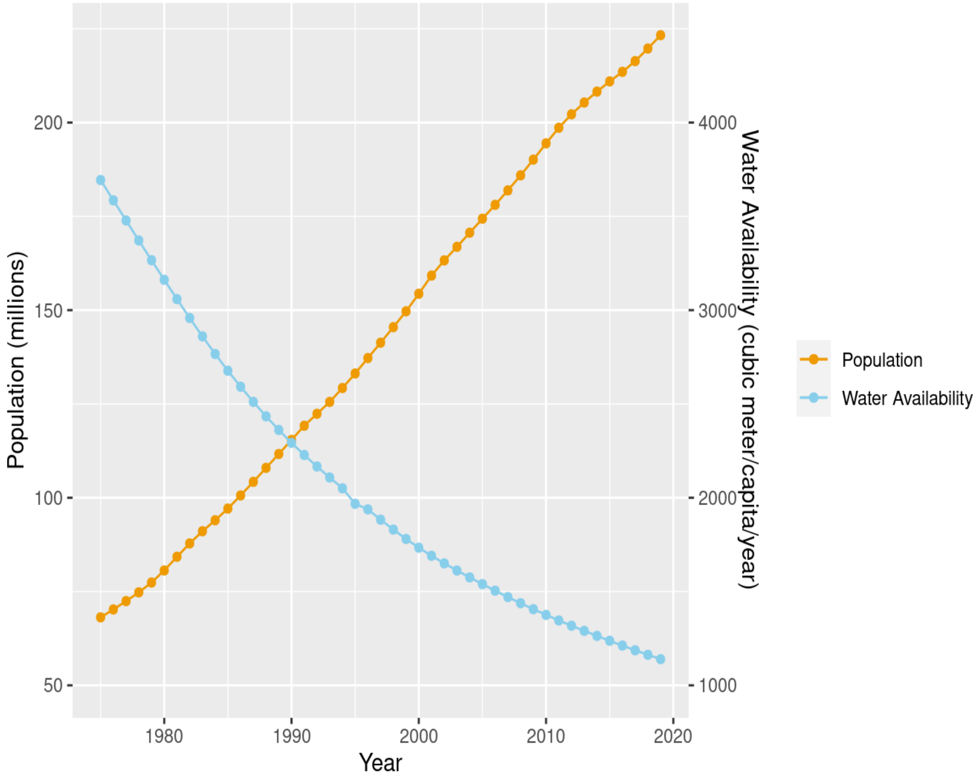
Figure 6: The precipitation trends of Pakistan from 1975 to 2019



The annual mean precipitation rates, on the other hand, display an overall decreasing frequency from 1975 to 2019. The sudden shifts in the rates indicate the risk of extreme weather events where the relatively lower precipitation from 1999 to 2002 represents the drought Pakistan experienced back then and higher than usual precipitation in 2010 and 2012 represents the floods that wreaked havoc in the past decade.

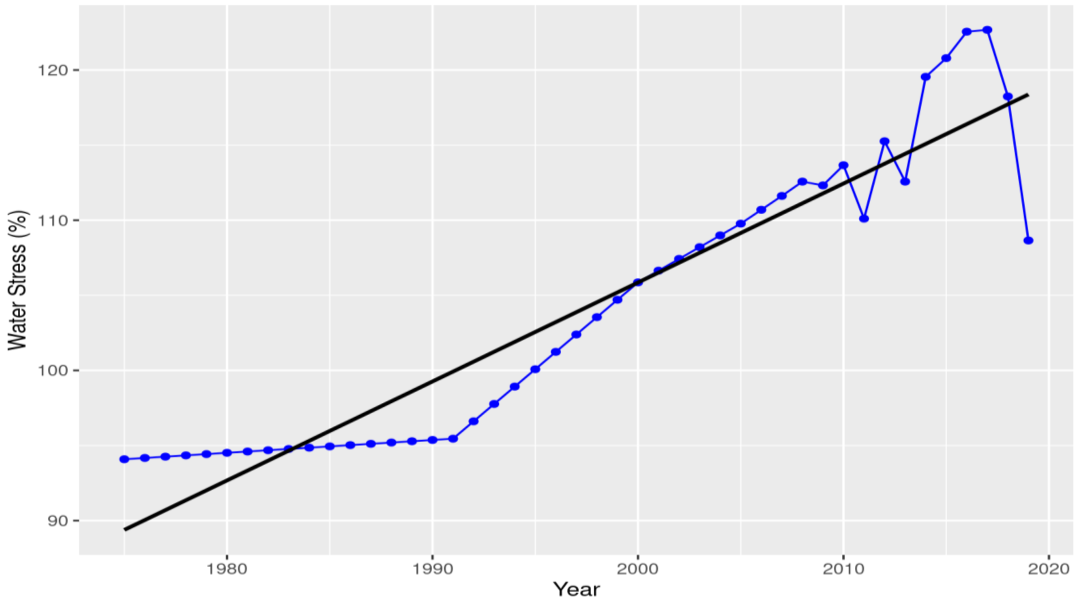
The variable "water security" was calculated using a deficit of "water availability" and "water demand" in the country. The measure of water availability indicates that the state's water wellsprings have depleted over the course of time. The population of Pakistan expanded from around 68.1 million in 1975 to more than 220 million in 2019 while the per-person water availability tumbled to about 1000 cubic meters per capita per annum in 2019 from nearly 4000 cubic meters per capita per annum in 1975, indicating an alarming rate of decline in the water resources of the country. The results of Pearson's correlation test show a significant (p-value < 0.01) strong negative correlation (coefficient: -0.96) between the population and per capita water availability in Pakistan for the data between 1975 and 2019.

Figure 7: Per capita water availability in Pakistan from 1975 to 2019



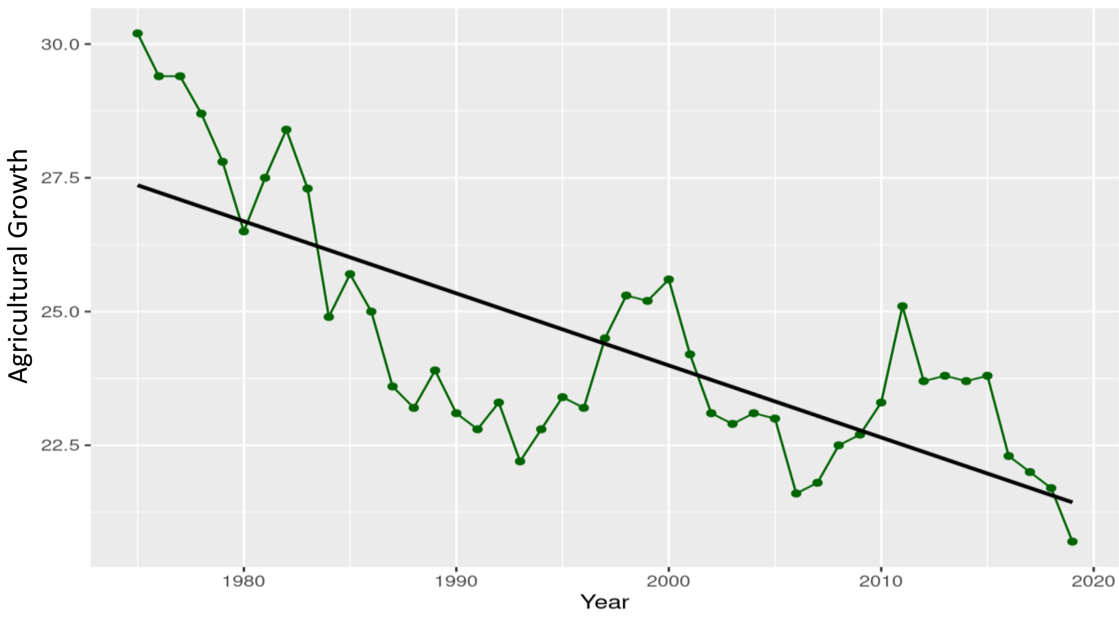
There is an inherent lack of open data for overall and sectoral water demand in Pakistan. Therefore, the measure of total freshwater withdrawals and agricultural withdrawals was taken to get a data view of water usage patterns in Pakistan. The results indicate a noticeable increase in the country's freshwater withdrawals over the last 45 years, implying elevated water demands in the country during this time period, and agricultural withdrawals represent over 90% of the total withdrawals, implying that irrigation water demand in Pakistan has also increased during the past few decades. Water scarcity is usually defined in the context of the water availability of a region and water security can be referred to as the relationship between total water availability and usage. As an average of 90% of total freshwater withdrawals account for agricultural withdrawals in Pakistan, the relationship between water availability and usage can be defined in the context of irrigation water security. Therefore, the measure of "water stress" was selected to compute the irrigation water security. Water stress in a region is referred to as the deficit between water availability and water demand. The data for mean water stress in Pakistan displays a sharp increase in water stress levels in the country since 1975, indicating considerably increasing water insecurity in the region.

Figure 8: Water stress (as deficit between water availability and demand) from 1975 to 2019



The dependent variable, agricultural growth, was selected as a measure of the performance of Pakistan's agricultural sector and it can be referred to as an increase in the productivity of agricultural land. Agricultural growth is usually measured through economic indicators, such as the GDP and the aggregate value added to the GDP. This study takes into account the average agricultural growth rate in Pakistan for correlation and regression in relevance with the GDP of Pakistan.

Figure 9: Gross value added by agriculture in the GDP of Pakistan from 1975 to 2019

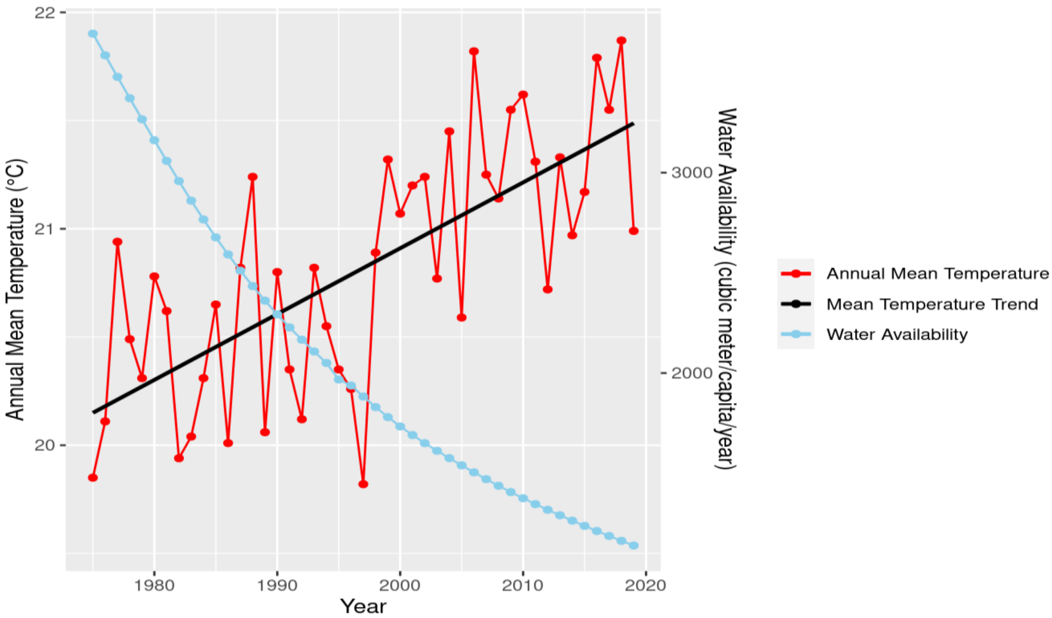


6.1. Correlational analysis

The correlational analysis was performed to explore the strength and nature of the relationship between different variables under study. Pearson's correlation test was performed for this scrutiny. The value for the coefficient of correlation (r) was noted to determine the strength and nature of the relationship, whereas the probability value (p-value) was observed to determine the significance of the relationship between the variables under study. A p-value lesser than 0.05 represents a "significant relationship" between any two variables. This analysis revealed the robust relationships between the temperature and the water availability, temperature and agricultural water withdrawals, precipitation and water availability, precipitation and agricultural water withdrawals, and water stress and agricultural growth rate in Pakistan.

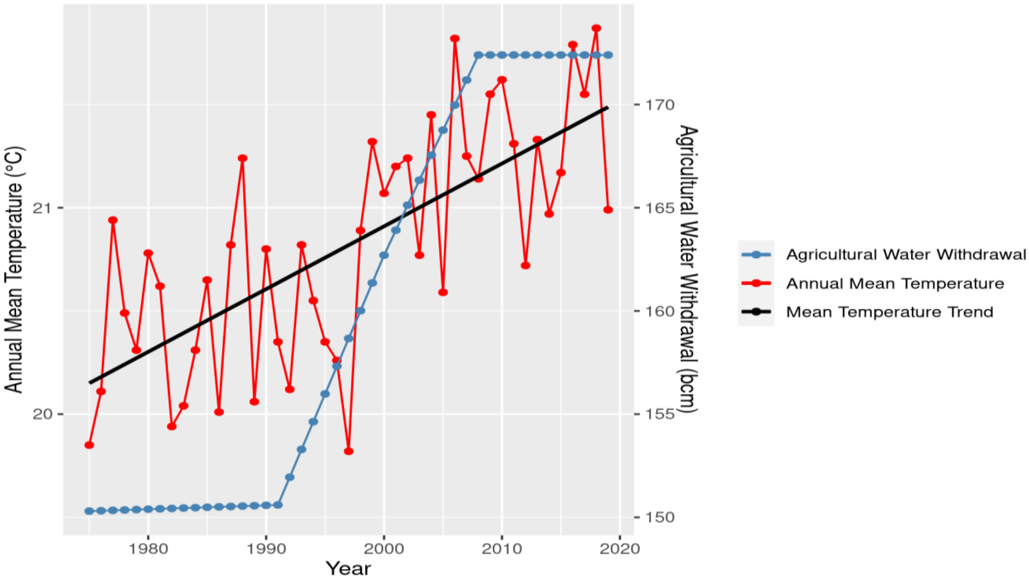
The results of the correlation between temperature and water availability in Pakistan indicated a significantly strong negative correlation (r: -0.8) between these two measures. The findings determined that with the increasing mean annual temperatures, the annual per capita water availability reduced in Pakistan between 1975 and 2019. The results of the correlation between temperature and agricultural water withdrawals in Pakistan indicated a significantly strong positive correlation (r: 0.7) between these two measures. The findings determined that with the increasing mean annual temperatures, the annual agricultural water withdrawals also increased in Pakistan over time.

Figure 10: Relationship between annual mean temperatures and annual per capita availability



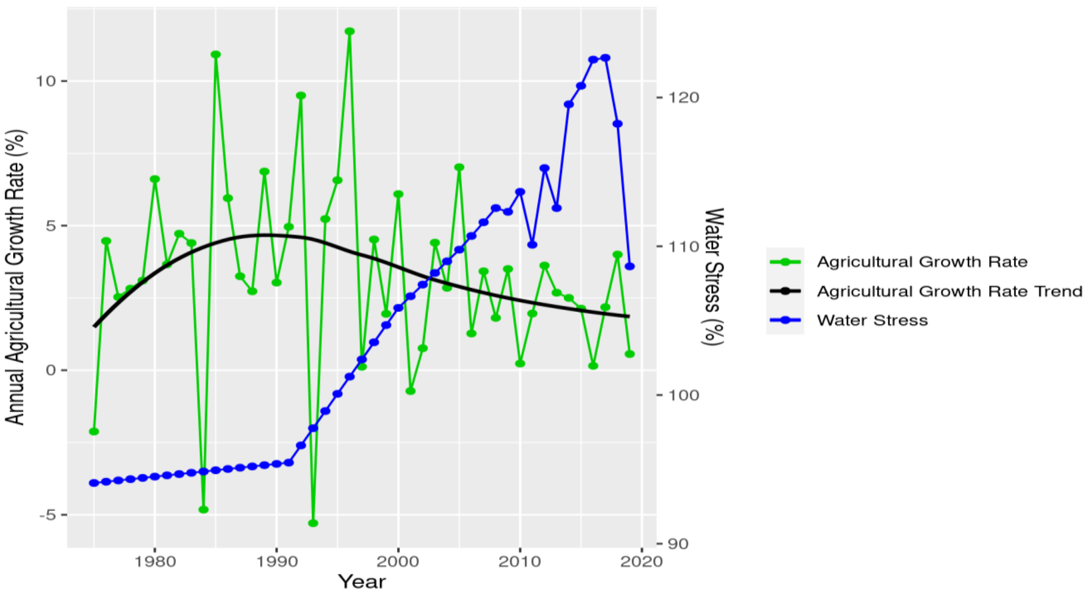
The results of the correlation between precipitation and water availability in Pakistan indicated a significant, yet weak positive correlation (r: 0.3) between these two measures. The findings revealed that the decreasing mean annual precipitation had an association with the annual per-person water availability in Pakistan between 1975 and 2019, however, the link between these two variables is weak which can be explained by the unprecedented fluctuations in the rainfall patterns of the country. The results of the correlation between precipitation and agricultural water withdrawals in Pakistan indicated an insignificant and weak negative correlation (r: -1.2) between these two measures. The findings revealed that the mean annual precipitation decreased over time while the annual agricultural withdrawals increased between 1975 and 2019, however, these changes did not necessarily take place in association with each other.

Figure 11: Relationship between annual mean temperatures and annual agricultural water withdrawals



The correlational results of water stress and agricultural growth rate in Pakistan indicated a significant, moderately strong negative correlation (r: -0.58) between these two measures. The findings determined that with the increasing mean annual temperatures, the annual agricultural growth rate decreased in Pakistan over the time period of 45 years. The probability was observed at a value less than 0.05, determining that water stress has a significant relationship with the agricultural growth rate of the country; however, this relationship is moderately strong which indicates that water stress might not be the only factor contributing to the decline of agricultural growth in Pakistan.

Figure 12: The relationship between annual water stress and annual agricultural growth rate in Pakistan



6.2. Regression Analysis

In addition to correlational analysis, a regression model was developed for quantifying the degree of impact climatic changes inserts on the irrigation water security of Pakistan and how this relationship affects the agricultural sector. The variable "climate change" was computed using the measures of average temperature and precipitation per annum, the variable "irrigation water security" was defined in the context of water stress, and the impact on agriculture was computed in terms of agricultural growth in the country. First, the single-factor logistic regression was run to quantify the impact of "climate change" measures, individually, on the mediating variable and through it, on the dependent variable. Second, a two-factor regression model was run, and mediation analysis was performed to get a holistic view of systemic linkages between the variables under study. The overall results of regression analysis determined that the variations in temperature and precipitation have aggravated the situation of water stress, in turn negatively affecting the agricultural growth in the country.

6.2.1. Single-factor Regression Model 1

Independent variable affecting Mediator: Mean Temperature → Water Stress
Mediator affecting Dependent Variable: Water Stress → Agricultural Growth Rate
Model: Mean Temperature → Water Stress → Agricultural Growth Rate

The value of the regression coefficient (R-squared) was observed to be -0.079 and the p-value was 0.01 for the regression model. These values indicate that the temperature-driven water stress explains a 7% decline in the agricultural growth of Pakistan and this model is highly significant in explaining the agricultural growth rate of the country.

Table 1: Results of the single-factor regression model with temperature as the independent variable

	Estimate	Std. Error	t value	Pr (>|t|)
(Intercept)	-19.76742	23.64250	-5.542	0.025
Mean Temperature	-5.83276	3.56787	-4.644	0.046
Water Stress	-9.52732	12.56974	-5.954	0.034
Mean Temperature: Water Stress	-7.24931	0.12194	-9.940	0.017

6.2.2 Single-factor Regression Model 2

Independent variable affecting Mediator: Mean Precipitation → Water Stress
Mediator affecting Dependent Variable: Water Stress → Agricultural Growth Rate
Model: Mean Precipitation → Water Stress → Agricultural Growth Rate

The value of the regression coefficient (R-squared) was observed to be -0.059 and the p-value was 0.04 for the regression model. These values indicate that the precipitation-driven water stress explains around 6% of the decline in the agricultural growth of Pakistan and this model is significant in explaining the agricultural growth rate of the country. It can also be inferred from this analysis that the measures of climate change combined explain a 13% decline in the agricultural growth of Pakistan by inducing stress on the water assets of the state from 1975 to 2019. As the average value added to GDP by agriculture in Pakistan was 24% from 1975 to

2019 and the total GDP during this time period was 4824.57 billion US$, it means that agricultural sector added a total of approximately 1157.9 billion US$ in the GDP of Pakistan and 13% of this amount was lost due to climate-induced water stress that triggered decline in agricultural growth of the country, accounting for a total of approximately 150.527 billion US$ or an annual average 3.5 billion US$.

Table 2: Results of the single-factor regression model with precipitation as the independent variable

	Estimate	Std. Error	t value	Pr (>|t|)
(Intercept)	-7.397e+01	3.367e+01	-5.174	0.040
Mean Precipitation	-9.129e-02	1.094e-01	-8.353	0.056
Water Stress	-9.527e-01	2.569e-02	-8.954	0.034
Mean Precipitation: Water Stress	-8.309e-04	1.031e-03	-8.062	0.017

6.2.3. Two-factor Regression Model

Factor 1 affecting Mediator: Mean Temperature → Water Stress
Factor 2 affecting Mediator: Mean Precipitation → Water Stress
Mediator affecting Dependent Variable: Water Stress → Agricultural Growth Rate
Model: Mean Temperature+ Mean Precipitation → Water Stress → Agricultural Growth

For the two-factor regression model, nonparametric bootstrapping was used to extrapolate the data of 45 years to run 1000 simulations. The results were computed using ACME and ADE values where ACME stands for "Average Causal Mediation Effects" and ADE stands for "Average Direct and Indirect Effects." Both of these methods were used to assess the relative contributions of different causal pathways to the overall effect of climatic changes on the agricultural growth rate. The ACME value, computed at 2.2504, signifies that the mediation exerts an overall impact 2.2504 times greater than the average effect of temperature or precipitation alone. This underscores the substantial influence of causal mediation on the ultimate outcome. Conversely, the ADE value, registered at -0.6202, denotes that the mean direct effect of climate change variables is 0.6202 times lower than the mean indirect effect of the mediation. This implies a comparatively weaker direct impact on agricultural growth rate when contrasted with the overall indirect effect. Notably, both ACME and ADE yielded p-values below 0.05, affirming the statistical significance of the established causal relationship between the variables in question.

In the regression analysis, the combined effect of 2.2504 ACME and -0.6202 ADE yielded a total effect of 1.6302. This summation represents the amalgamation of direct and indirect effects. The resultant total effect suggests that climate-induced water stress exerts an overarching impact, 1.6302 times greater than the average effect of individual pathways. Thus, the findings underscore the potent influence of climate-driven water stress on the decline of agricultural growth in Pakistan.

7. Conclusion and recommendations

Pakistan is among the most vulnerable countries in South Asia exposed to the escalating threats of climate crises. This study was developed to examine the impact of climatic changes on irrigation water security, seeking to comprehend the implications for agricultural growth and, consequently, food security in Pakistan. The primary objective of this research was to scrutinize the effect of temperature and precipitation changes on the deficit of water availability and demand. The secondary objective was to ascertain how and to what extent this relationship influences the agricultural growth of the country. To achieve these objectives, a two-factor regression model was utilized for the mediation analysis. The results of the study revealed that the changes in temperature and precipitation have triggered an increase in water stress, in turn negatively affecting the agricultural productivity in the country and this decline in agricultural accounts for a total of 150.3 billion US$ (2022 exchange rate) during the time period of 1975 and 2019. The third and last objective of the study is to address the dire need to encourage adaptive measures on both policy and operational levels.

This study presents a policy perspective to guide future endeavours that address the demand side of the management of risks posed by climate change on irrigation water security in order to facilitate the climate change adaptation process. Unfortunately, there is no "correct" or "best" way to adapt to climate change; adaptation rather means involving a range of strategies over the short-term and long-term solutions. The National Water Policy of Pakistan (2018) lacks the guidelines to encourage water-sensitive urban infrastructure, manage the production and trade of water-insensitive crops, and adaptation of water system frameworks to changing climatic regimes in order to mitigate the risks related to water-related extreme events. Therefore, this policy needs revisions to include customized and location-specific solutions for managing the aggravating water crises in Pakistan. Moreover, policymakers need to formulate and implement provincial climate adaptation strategies in order to guide the action-oriented resolution of water problems. To achieve this, the "Pakistan Climate Change Act, 2017" needs to be revised for sector-wise adaptation to climate-driven water stress in order to conserve the depleting water resources at local, provincial or state, and national levels. There is also a need to focus on efficient decision-making to plan for sustainable adaptation pathways in the face of uncertainty and risks related to anticipated effects of climatic changes given that unsustainable adaptation pathways have been leading to disastrous ramifications for crop yield across the globe.

Pakistan has an agrarian economy, and the efficiency of the country's agribusiness depends on sufficient availability of quality water. However, the supply of irrigation water has become more privatized since the 1980s where physical targets are prioritized rather than capacity building, helping the elites and depriving the poor farmers of their rightful access to irrigation water. There are more than 562,000 private tubewells in the country that are exploiting its water resources beyond their capacity. Therefore, Pakistan needs to reassess its water governance in order to ensure equitable and rightful access to water resources, keeping in view the adaptation of water conservative agricultural practices and tumbling water availability. Moreover, there is also a need for a justice-centred approach to climate change adaptation where all people regardless of race, financial status, or social position get the opportunity to invest in climate-smart adaptation measures.

Climate change has compromised the irrigation water security in Pakistan, but climate-smart agriculture has the potential to tackle climate-induced irrigation challenges; this approach aims to incorporate agricultural expansion and climate receptiveness to achieve the agricultural growth targets and ensure the food security of the population under shifting weather regimes. One possible climate-smart solution is to redefine the agro-climatic zones in the country as the current classification follows the historical climate patterns, rendering it obsolete. The government needs to allocate crop areas in different agro-climatic zones on the basis of water availability and ensure the mindful use of water resources. In areas with groundwater stress, there is a desperate need to review cropping patterns and encourage less water-consuming crops. In addition, there is a need to introduce water-conservative agricultural practices, such as soaker hoses and drip irrigation, in place of conventional techniques, such as flood irrigation. According to a report by the United Nations Food and Agriculture Organization, farmers in Pakistan use two to three times more irrigation water than the recommended requirement for rice cultivation, and when we export it, we are actually exporting virtual water. Therefore, the policymakers need to devise ways to ensure that the farmers use water for irrigation according to crop requirements without affecting the agricultural yield. This technique is referred to as intelligent irrigation or plant-responsive irrigation and it has the potential to intercept over-irrigation in order to prevent the wastage of this precious resource. A lot of companies are now shifting their focus towards plant-responsive water delivery systems due to their increasing demand. These systems work at low pressure (≈1-2 PSI) and low energy (even a single solar panel is adequate), employing the knowledge of the organic chemistry of plants to work in harmony with nature. These systems have the potential of doubling the agricultural yield while using 50% less water and they also regenerate soil health as they reduce agrochemical usage and prevent tillage.

The government of Pakistan also needs to take initiatives to promote investment in these systems and allocate a portion of agricultural subsidies where instead of giving cash, these systems are installed for small-holder farmers. Moreover, researchers can make evidence-based models to imitate the anticipated impact of climate change using information technology, Geographic Information Systems (GIS), and remote sensing, in order to test the validity and efficiency of different climate adaptation and mitigation policies and guide the strategies for meticulous irrigation water efficiency to enhance water productivity. There is also a desperate need to generate accurate data about soil moisture, crop requirements, and climate-induced water challenges that affect agricultural growth in different zones. The data on water demand, particularly province-wise and sector-wise information, is inadequate to carry out thorough research on climate-driven water stress. In addition, more research is required on the subjects of water pricing and water-use efficiency in order to develop and implement sustainable water conservation policies. In a nutshell, Pakistan needs to promote climate-smart agricultural practices, devise a climate-alert policy, and educate the farmers about water-conservative techniques for irrigation. The recommendations of this study address the demand-side management of the challenges to irrigation water security posed by shifting climate patterns and focus on improving water-use efficiency in the agricultural sector to make sure that every drop counts.

Declaration of conflict of interest

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