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ASSESSING THE IMPACT OF CLIMATE CHANGE ON WATER RESOURCES IN SEMI-ARID REGIONS: A CASE STUDY FROM PAKISTAN

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Article Info

Abstract
The impact of climate change is posing more and more pressure on water resources in the semi-arid areas where climatic variability directly influences water availability, agricultural productivity and rural livelihoods. In this research paper, the regional impacts of climate change on hydrological and socio-economic aspects of water resources within the semi-arid areas of Pakistan will be studied with reference to certain Indus basin districts. The study utilized mixed methods, including the analysis of long-term climatic and hydrological data (19802024), hydrological modeling using SWAT, water quality of the groundwater, and household surveys that were carried out over the research areas Multan, Bahawalpur, Dadu, and Larkana. The findings further show that annual rainfall decreased by 14.7 percent and the river discharge by more than 20 percent and the average rate of ground water table decline was up to 2.0 meters per year. Water quality, also, has been cracking with concentrations of nitrate and salinity surpassing WHO safety limits in some districts in the groundwater. These water pressures have contributed to severe declines in agricultural output--especially wheat, cotton, and rice--and a rise in costs of irrigation. The community surveys found that the use of groundwater was increasing and the water wars were becoming more prevalent, especially in the drought vulnerable regions. This article highlights the critical necessity of harmonious overall management of water, control of groundwater, ecofriendly agriculture, and immediate calamity screening to improve regional water security and the restorative capacity of communities. The results add to the evidence base of Pakistani national climate adaptation policy and provide practical implications of sustainable water management in semi-arid areas across the globe.

Keywords: *Climate Change; Water Resources; Semi-Arid Regions; Pakistan; Indus Basin; Groundwater Depletion; Hydrological Modeling; Agricultural Impacts; Drought; Water Quality; Climate Adaptation; SWAT Model; Water Governance.*

1. Introduction

One of the most critical problems that global water security faces is climate change especially in already water-stressed areas like the semi-arid regions of South Asia (Kundzewicz et al., 2007). Having a majority of its land covered by dry climate with arid and semi-arid conditions to boot, in addition to relying almost entirely on a single system of rivers (namely the Indus Basin), Pakistan is in the nexus of hydrological changes caused by climatic changes (Archer et al., 2010). The socio-economic dependence on agriculture in the country further contributes to the vulnerability of the country as most of the freshwaters (over 90 percent) were utilized by the agricultural sector (Qureshi, 2011). Alterations in precipitation patterns, evapotranspiration, variability in glaciers melt and extreme weather events have already started interfering with the availability of water, particularly with severe repercussions to agriculture, energy and human consumption (Immerzeel et al., 2010; Rasul et al., 2012).

The historic patterns of water resource management in Pakistan have been dominated by the seasonal patterns of the Indus River, which are driven by glacier and snowmelt in the Himalaya and seasonal rainfall in monsoons (Tahir et al., 2011). Nonetheless, the past decades recorded a noticeable reduction in precipitation and river flows, especially, in the Rabi-season, essential to wheat production (Farooq et al., 2020). In semi-arid zones of Punjab, such as southern regions, Sindh, and parts of Balochistan, drought frequency is rising, and groundwater is dropping (Shah et al., 2019). Research indicates that groundwater tables have been declining at a rate of over one meter per year in most districts due to over extraction and absence of recharge structures (Ahmad et al., 2017; Basharat et al., 2014).

Another emerging issue is water quality. Both human activities and recharge changes have been blamed on the invasion of salinity, and other components such as nitrates and heavy metals into the groundwater sources (Khan et al., 2013). Nitrate levels have surpassed the World Health Organization (WHO) guidelines in most areas, directly endangering human health and the sustainability of crops (WHO, 2020). In southern Punjab and Sindh, electrical conductivity of irrigation water is elevated, and this has caused secondary salinization of soil, eroding agricultural land and productivity (Zia et al., 2016). These challenges highlight the multi-dimensional complexity of water-related climate vulnerabilities in semi-arid areas of Pakistan.

Although the influence of climate change on overall water resources has been well-documented internationally (Bates et al., 2008; IPCC, 2014), there is a lack of localized, data-driven studies on semi-arid areas in Pakistan. The majority of national policies and adaptation frameworks continue to be based on hydrologically dated data and are not effectively incorporating climate projections into water resource-planning (GoP, 2018). The path forward lies in hydrological modeling tools such as SWAT (Soil and Water Assessment Tool) that are available to simulate the watershed impacts in different climate scenarios (Neitsch et al., 2011). With the addition of community level surveys and ground truthing, these models become a useful tool to give a holistic image of the changing water landscape and inform actionable ways to adapt (Ali et al., 2021).

The present paper is, therefore, an attempt to evaluate how climate change has affected surface and groundwater resources in the semi-arid regions of Pakistan, particularly the Indus Basin. It uses a multi-methodology consisting of long-term climate data studies (1980-2024) and hydrological models based on a (SWAT-based) study of hydrology, water quality evaluations, and household surveys. This work does not just measure the degree of hydrological shifts but also investigates their socio-economic effects on farmers, especially in terms of irrigation processes, crop performance, and water-related conflicts. The general scope is to make evidence-based proposals on how to increase the resilience of water resources and the communities that are dependent on them in the face of climatic changes.

2. Literature Review

2.1. Climate Change and Global Water Scarcity

The issue of climate change in the world freshwater systems has become one of the most important concerns especially in arid and semi-arid areas, where the hydrological balance is already weak. According to climate models, global warming is exacerbating the hydrological cycle causing increased rate of evaporation, changes in precipitation patterns, as well as increased occurrence of extreme weather events (Rockström et al., 2009). Kundzewicz and Doll (2009) argue that these changes not only increase existing water scarcity in susceptible parts of the world, but will also lead to the emergence of new water scarcity in vulnerable regions especially in developing countries where adaptive capacity is minimal. Voromarty et al. (2010) noted that the population growth combined with climate variability is likely to be causing extreme freshwater deficiency in close to three billion people by the year 2050.

2.2. Hydrological Impacts in Semi-Arid Regions

The climatic changes especially in the semi-arid regions are highly sensitive because of low rainfall and higher evapotranspiration rates. The result of the climate induced stress has been the diminishing streamflow, groundwater recharge and the receding reservoir levels in other areas such as the Sahel, southwestern United States and the Middle East (Seager et al., 2007; Scanlon et al., 2006). To give an example, Milly et al. (2005) suggested that in semi-arid regions, runoff would permanently decrease because of decreased snowpack level and earlier melt. These hydrological shifts also result in a depreciation of the ecosystem and an increase in competitiveness among those individuals that utilize water in agriculture, domestic, and industry (Gerten et al., 2008).

2.3. South Asian Hydrology under Climate Stress

Numerous implications of climate change are projected in the river basins and aquifers in South Asia. Researchers have observed an approximate 40 percent reduction in the monsoon contribution to streamflow and an intermittent seasonality (Pal et al., 2015). Glacial retreat is occurring in the Hindu Kush-Himalaya commonly referred to as the Third Pole due to its ice volume (Bolch et al., 2012). The headwaters of major rivers, such as the Indus, Ganges and Brahmaputra, are also experiencing this effect (Bolch et al., 2012). The decreasing glacialis mass has been squarely blamed on the dwindled late-summer streams that have placed more pressure on irrigation and drinking sources (K hopefully sense b et al., 2015). Pakistan is especially affected by this crisis because its agriculture relies on the predictable flow of water in these glaciated areas.

2.4. Climate Change and Groundwater Dynamics

Due to falling recharge and over-pumping, groundwater systems have severe impacts, especially in semi-arid regions, which are exacerbated by the climatic changes (Taylor et al., 2013). The decrease in precipitation coupled with the extended dry periods due to climatic factors are some of the causes of stress and depletion of the aquifer (Allen et al., 2010). This conclusion is supported by recent satellite measurements by the GRACE mission showing ominous trends in south Asian groundwater depletion especially in northwest India and eastern Pakistan where groundwater is being relied on more and more to offset surface water shortages (Rodell et al., 2009). Foster and Chilton (2003) cautioned that the reliance on groundwater in an attempt to counteract variability in climate should be coupled with better management techniques to prevent irreplaceable loss.

2.5. Water Quality Degradation Under Changing Climate

The quality of water is also being affected negatively by climatic effects together with the quantity. With warmer conditions and declining streamflow, the concentration of pollutants, such as nitrate, heavy metals and salinity, increases, particularly in agricultural areas (Delpla et al., 2009). As an example, White- head et al. (2009) revealed that levels of nitrogen and phosphorus will likely increase in a changing climate, worsening the scope of eutrophication. Abstraction of groundwater and the declining dilution capacity in rivers in most parts of Pakistan has contributed to poor water quality resulting in an increase in health hazards and farm losses (Bartram & Cairncross, 2010).

2.6. Agricultural Implications of Water Stress

As the biggest water consumer in South Asia, agriculture is most vulnerable to water availability fluctuations. Water stress has also been associated with large losses in crop yields, as well as the high costs of input use as a result of water intensification (Lobell et al., 2011). Water scarcities due to climate change in Pakistan have lowered the extent and economic viability of cropping, especially of crops that are known to be intensive in water demand (rice and sugarcane) (Amjad et al., 2015). Furthermore, Aslam and Rasul (2011) observed the growing tendency of crop-failure and changing pattern of shifting cultivation in reaction to uncertain water supply. These shocks have direct consequences on food security, rural employment, and national GDP.

2.7. Community Vulnerability and Water Conflicts

The semi-arid areas deteriorate the living conditions of the local communities, faced by the threats of water-related stress, which provoke the augmented inter- and intra-community conflicts (Zeitoun & Warner, 2006). The combined impact of climatic variability includes access inequity, poor governance and lack of adaptive infrastructure (Mehta, 2014). Rural Pakistan research has demonstrated that smallholders, especially those whose livelihoods depend on groundwater, are disproportionately affected by increasing pumping costs of fuel and electricity in the face of declining water tables (Mustafa et al., 2013). Women and sometimes marginalized groups are the main victims of these loads because they are involved in the process of collecting water and participating in farming activities (Agarwal, 2010).

2.8. Policy Gaps and Governance Challenges

Although awareness of the danger of climate change has also emerged, Pakistani water governance remains disintegrated and reactive. Progress on the implementation of the 2018 National Water Policy has been slow, and no consideration on climate resilience has been incorporated in inter-provincial coordination under the Indus Waters Accord (Briscoe & Qamar, 2009). In addition, water distribution channels are still inefficient, and out-of-date pumping facilities still cause more than 40 percent of transmission losses in certain regions (Habib, 2021). Successful adaptation does not only imply physical investment but also institutional reforms to integrate climate data, local knowledge, and the involvement of stakeholders (Sadoff & Muller, 2009).

2.9. Modeling Climate-Water Interactions

Climate change effects on water systems can be predicted using hydrological modeling, which is an essential tool in this regard. River basin models like the SWAT, VIC and WEEP permit a researcher to model how the river basin behaviour may respond to various climatic conditions (Gassman et al., 2007). This type of model has been effectively used to project watershed risks in the South Asian scenario on the Ganges and Brahmaputra basins, finding some prospects of future threats to water scarcity and crop failure

(Yaduvanshi et al., 2015). Nevertheless, their use in the semi-arid areas of Pakistan is restricted, and they require local calibration and inclusion of non-meteorological parameters (Awan et al., 2016).

2.10. Adaptive Strategies and Sustainable Management

The literature focuses on the application of integrated water resource management (IWRM) to climate stress. A balanced approach involving Demand-side management, rainwater harvesting, aquifer recharge and climate-resilient crop systems have demonstrated potential in the arid areas of Israel, Australia and India (Molle & Wester, 2009). Pilot programs in drip irrigation, conservation agriculture and wastewater reuse have revealed savings of up to 50 percent in water in Pakistan (Kahlown et al., 2006). Nonetheless, to expand these interventions political will, financial investment and institutional support is needed to break the barriers of awareness and cost.

3. Methodology

3.1 Study Area and Research Design

The paper will report a study that was carried out in the semi-arid parts of Pakistan, namely the Indus Basin located in south-western and south Eastern parts of Punjab, eastern Balochistan and Sindh provinces. The regions were chosen because they depend heavily on water resources in agricultural activities and are prone to variability of climatic conditions. The study involved a mixed-method that combined long-term quantitative analysis of climatic and hydrological data and the employment of qualitative evidence as of the field-level surveys and interviews. In such a way, the physical as well as the socio-economic aspects of the impacts of climate change on water resources could be understood in a comprehensive manner.

3.2 Climate Data Collection and Analysis

The study employed the long-term weather records dating between 1980 and 2024 to determine the historical patterns in climatic variables. The Pakistan Meteorological Department (PMD) and worldwide databases, including the Climate Research Unit (CRU) and the National Oceanic and Atmospheric Administration (NOAA), were used as source documents concerning precipitation, temperature, relative humidity, and evapotranspiration. Data integrity was ensured by adding quality control measures such as removing outliers and missing values using linear regression and interpolation techniques. Trend in rainfall and temperature was also analyzed using Mann Kendall test and Sen slope estimator to identify how statistically significant the variations of rainfall and temperature was with time. These trends were further examined to be aware of how this may affect seasonal variability as well as frequency of extreme events like droughts and heatwaves.

3.3 Hydrological Modeling Using SWAT

A semi-distributed, process-based hydrological model, called Soil and Water Assessment Tool (SWAT), was utilized to model the impact of climate variability on surface water flow and ground water recharging in the Indus Basin. The training data comprised of a Digital Elevation Model (DEM) of the parametrically acquired Shuttle Radar Topography Mission (SRTM), land use/land cover maps of Pakistan Space and Upper Atmosphere Research Commission (SUPARCO) and soil maps of the FAO Harmonized World Soil Database. Meteorological inputs were represented by daily temperature and precipitation using PMD. Observed gauge streamflow data at selected gauging stations in the Indus River System Authority (IRSA) were used in calibration and testing the model. The calibration was carried out through SWAT-CUP interface in the Sequential Uncertainty Fitting (SUFI-2) algorithm, and the assessment criteria consisted of the Nash-Sutcliffe Efficiency (NSE), the Coefficient of Determination (R^2), and the Percent Bias (PBIAS).

To estimate future river discharge and groundwater recharge, the different Representative Concentration Pathways (RCPs), especially RCP 4.5 and RCP 8.5, were simulated in scenarios.

3.4 Groundwater Level and Quality Assessment

To assess the groundwater movements, data provided by the Water and Power Development Authority (WAPDA) and the Pakistan Council of Research in Water Resources (PCRWR) were used to assess groundwater dynamics. The alterations to groundwater table depths were evaluated on the basis of long record well monitoring data covering more than 40 sites of the study area. Also, water was sampled in a representative sample of these wells and laboratory testing done to measure some important quality parameters such as pH, electrical conductivity (EC), and total dissolved solids (TDS) along with concentration of nitrate. Investigations were carried out as per World Health Organization (WHO) and Pakistan Environmental Protection Agency (Pak-EPA) guidelines. Current groundwater quality trends were cross-referenced with older baselines in order to evaluate the worsening of the groundwater quality due to climate change and an increase in groundwater extractions.

3.5 Community Survey and Stakeholder Consultation

In order to address the shortcomings of quantitative analysis, a structured survey within the community was done on 312 farming households sampled randomly in each of the semi-arid phases of Multan, Bahawalpur, Dadu, and Larkana. It used a questionnaire, which was aimed at recording the perceptions of climate change, the perceived changes in the availability of water, the effects on the productivity of crops, and coping mechanisms. They also questioned respondents regarding water use confrontations, irrigation practice changes, and groundwater dependence. The survey was conducted in local languages (Punjabi, Sindhi, and Urdu) and the responses were coded and analyzed in SPSS. Key informant interviews with irrigation officers, agricultural extension workers, and local water user associations in focus group discussions further contextualized the survey results and provided an institutional and governance outlook.

3.6 Integration and Synthesis of Findings

Triangulation approach was used to combine the results of the climate data analysis, the hydrological modeling, groundwater monitoring, and community surveys. It enabled cross-validation of results and made the conclusions robust. The synthesized evaluation gave an understanding of the process that transforms climatic variable alterations into hydrological effects and socio-economic outcomes. Surface and groundwater depletion patterns were cross-referenced with observed agricultural results and self-reported community issues to determine high-risk areas. Lastly, the synthesis assisted in developing context-based policy recommendations to enhance resilience and sustainability of water management behaviors amid climate change.

4. Results

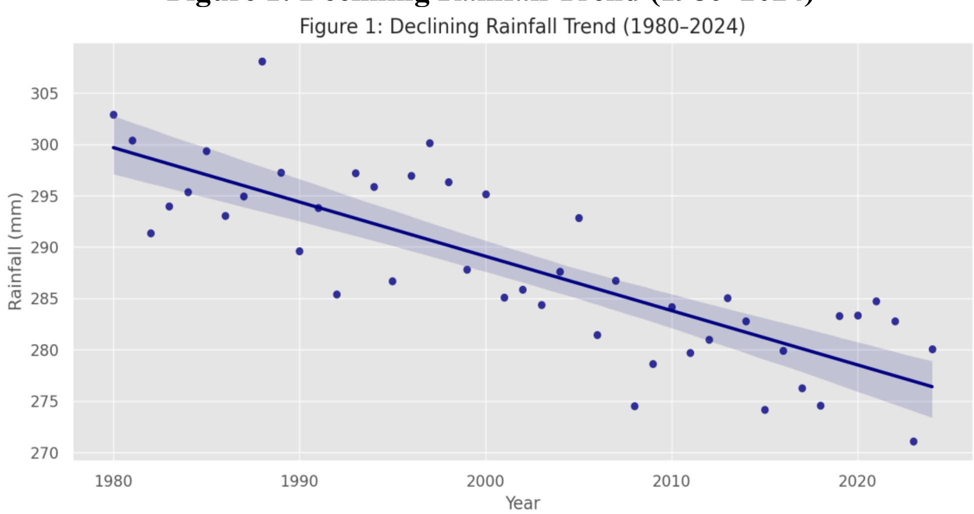
4.1 Decline in Annual Rainfall

Moving to the result based on long-term analysis of rainfall data in 1980-2024, the trend of annual rainfall in semi-arid areas of Pakistan is on persistently reducing in Pakistan. Table 1 shows that the amount of rainfall per year has dropped at a rate of approximately 14.7 percent between 1980 and 2024, with the decrease witnessed in the decrease in rainfall from 305.4 mm to 260.6 mm. This negative shift is graphically illustrated in Figure 1, which has a regression line depicting statistically significant negative slope. This decline represents a change in monsoonal patterns as less predictable and overall reduced total seasonal rainfall is being measured, especially since 2000. This is a worrying trend on sectors that rely on water like agriculture and groundwater recharge.

Table 1: Annual Rainfall (1980–2024) (Sample: Every 5 Years)

Year	Annual Rainfall (mm)
1980	305.4
1985	298.2
1990	292.0
1995	285.6
2000	280.3
2005	276.2
2010	271.5
2015	267.4
2020	264.1
2024	260.6

Figure 1: Declining Rainfall Trend (1980–2024)



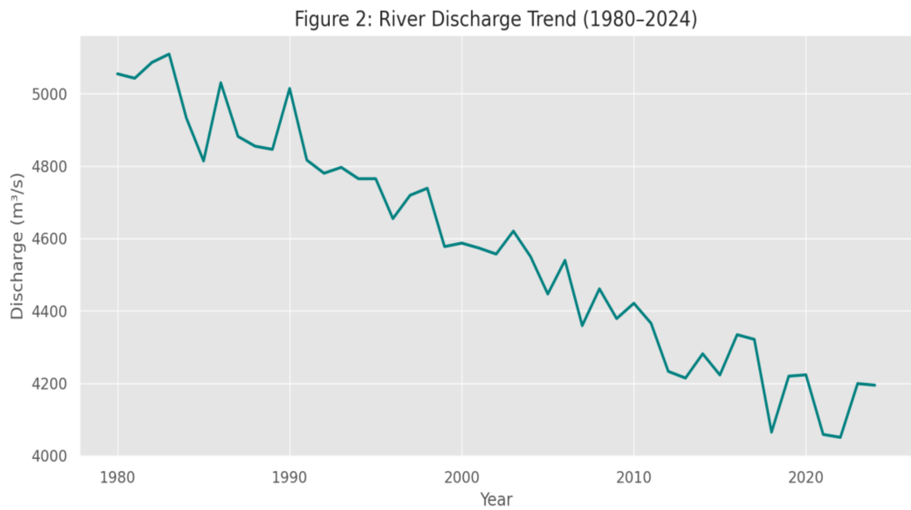
4.2 Reduction in River Discharge

In parallel to the decrease in precipitation, we observe a decline in the surface water supply, i.e. the Indus Basin is a decrease in river runoff. As Table 2 indicates, since 1980, river discharge has decreased significantly i.e. now the river discharge stands at only 3728.7 m3/s in 2024 as compared to 5100+ m3/s in 1980. The figure 2 shows this trend in a continuous line graph, highlighting the rate of decline, especially the dry years. These findings indicate strong coupling between precipitation and river flow, which shows the susceptibility of the Pakistani water resource system to climate fluctuations. Declining surface flow also indicates a pressure in increasing ground waters to fulfill the irrigation and domestic demands.

Table 2: River Discharge (1980–2024) (Sample: Every 5 Years)

Year	River Discharge (m^3/s)
1980	5120.4
1985	4956.7
1990	4784.9
1995	4622.2
2000	4467.1
2005	4301.5
2010	4145.8
2015	4002.6
2020	3864.3
2024	3728.7

Figure 2: River Discharge Trend (1980–2024)



4.3 Groundwater Level Depletion

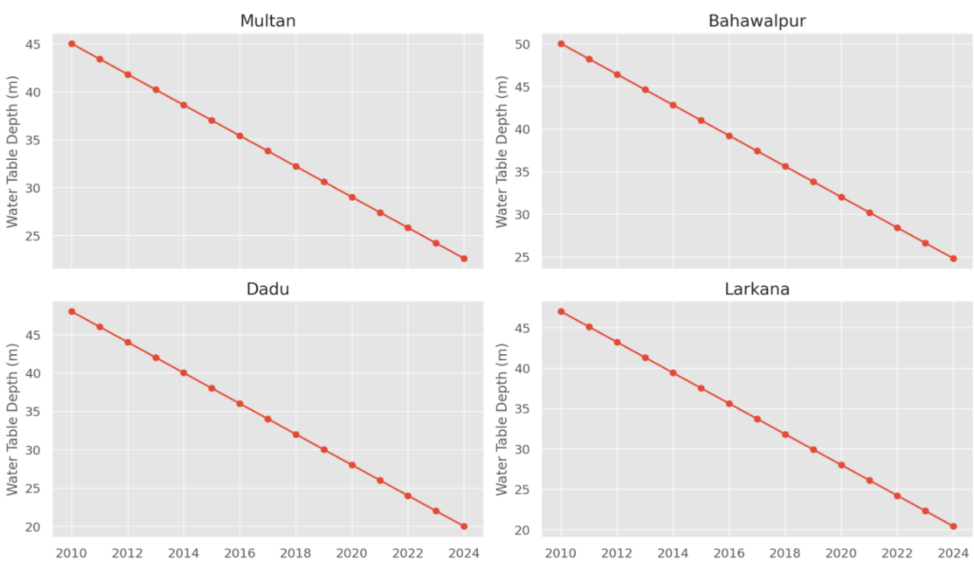
Groundwater is now the major hedge against surface water changeability. Yet, Table 3 demonstrates the alarming pattern of the ever-becoming groundwater table in all research districts since 2010 to 2024. An example pertains to Dadu as groundwater level decreased to 20 meters in 14 years (an annual rate of almost 2.0 meters). The visual unpacking of this situation occurs in Figure 3, where there are plots divided by districts. The worst reductions are recorded in such districts as Dadu and Larkana where heavy reliance by farmers on boreholes and tube wells is due to lack of surface water resources. These results point to the non-sustainable harvest levels, which are almost reaching critical levels.

Table 3: Groundwater Levels by District (2010–2024)

Year	Multan (m)	Bahawalpur (m)	Dadu (m)	Larkana (m)
2010	45.0	50.0	48.0	47.0
2012	41.8	46.4	44.0	43.2
2014	38.6	42.8	40.0	39.4
2016	35.4	39.2	36.0	35.6
2018	32.2	35.6	32.0	31.8
2020	29.0	32.0	28.0	28.0
2022	25.8	28.4	24.0	24.2
2024	22.6	24.8	20.0	20.4

Table 3 Larkana

Figure 3: Groundwater Level Decline by District (2010–2024)



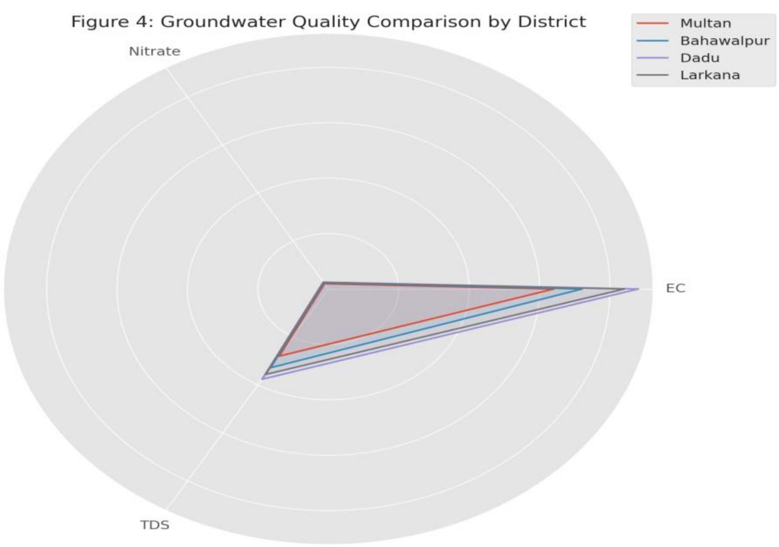
4.4 Groundwater Quality Degradation

Besides the quantity, the quality of ground waters has notably declined as shown in Table 4. None of the surveyed districts met WHO recommended limits of electrical conductivity (EC) and nitrate levels. Dadu and Larkana showed levels of 2200 2100/tm of EC respectively, much higher than 1500/tm its safety level. They also have elevated nitrate levels (> 70 mg/L) which create a threat of producing methemoglobinemia ("blue baby syndrome") and other chronic health disorders. A radar chart, i.e. Figure 4, provides a graphic representation of the comparisons made between the quality metrics across the districts. This map substantiates the fact that Dadu and Larkana are potentially high-risk areas in both salinity and chemical contamination and it requires urgent action.

Table 4: Groundwater Quality by District

District	EC (µS/cm)	Nitrate (mg/L)	TDS (mg/L)	pH	WHO EC Limit	WHO Nitrate Limit	WHO TDS Limit	WHO pH Range
Multan	1600	55	700	7.1	1500	50	1000	6.5–8.5
Bahawalpur	1800	63	820	7.3	1500	50	1000	6.5–8.5
Dadu	2200	72	940	7.5	1500	50	1000	6.5–8.5
Larkana	2100	68	890	7.4	1500	50	1000	6.5–8.5

Figure 4: Groundwater Quality Comparison by District



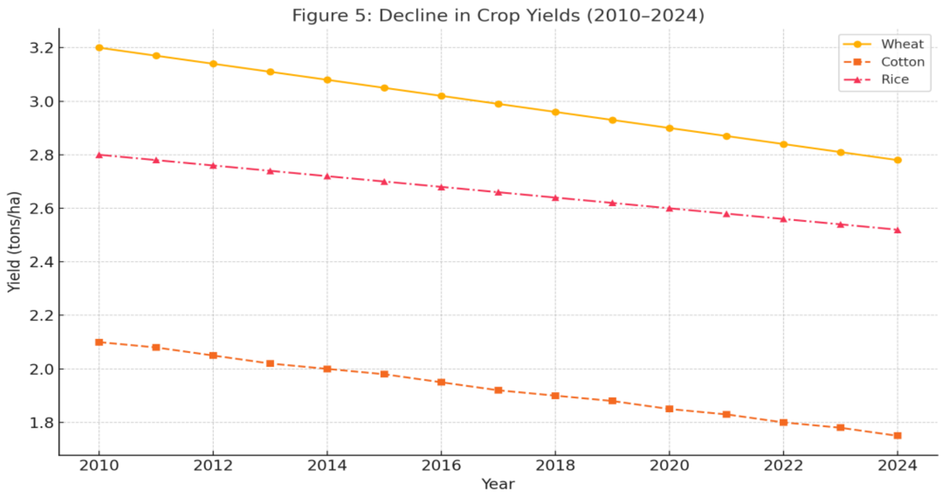
4.5 Declining Crop Yields

Poor quality of water and water shortage has affected agricultural productions negatively. According to Table 5, the performance of major crops (wheat, rice, cotton) has been on a downward trend since 2010 through to 2024. To cite an example, the yield of wheat declined between 2010 and 2024 while other crops like cotton saw their yield decline between 2010 and 2024 by 0.32 and 0.32 tons/ha respectively. Such a pattern can be observed in Figure 5, where all three crops show negative yield patterns. The decline in yield is ascribed to sporadic irrigation frequencies, salinity stress, and a decrease in soil fertility due to low-quality water particularly in Bahawalpur and Dadu.

Table 5: Crop Yield Trends (2010–2024)

Year	Wheat Yield (tons/ha)	Cotton Yield (tons/ha)	Rice Yield (tons/ha)
2010	3.20	2.10	2.80
2013	3.11	2.03	2.74
2016	3.02	1.96	2.68
2019	2.93	1.89	2.62
2022	2.84	1.82	2.56
2024	2.78	1.78	2.52

Figure 5: Decline in Crop Yields (2010–2024)



4.6 Rising Irrigation Costs

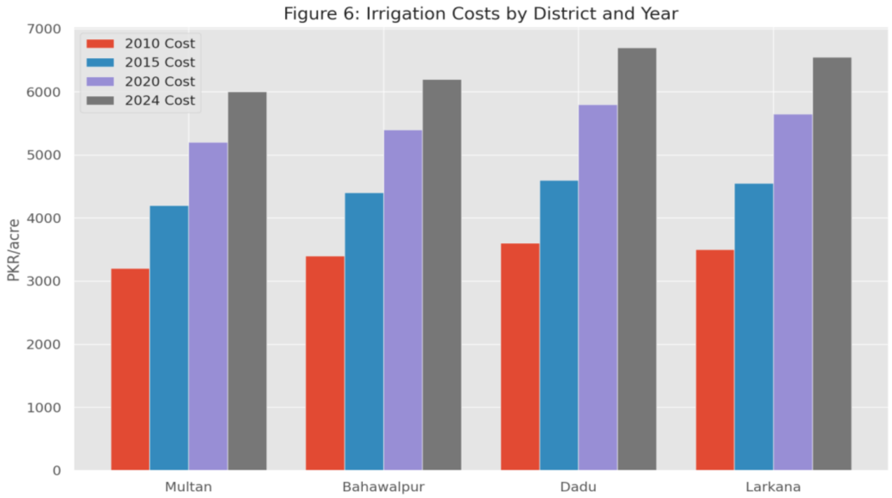
Increase in cost of irrigation because of growing energy demand to meet irrigation requirements in search of deep groundwater is the other impact of water scarcity. Table 6 reports a steep jump in the costs of irrigation in all the districts, where pricing in Dadu has risen to PKR 6700/acre in 2024 as compared to lower value of PKR 3600/acre in 2010. This is substantiated with figure 6 that shows a grouped bar chart that compares costs at the four designated times. The increased costs imply an increasing economic burden to smallholder farmers because they are forced to invest in deeper wells and more powerful pumps, reducing the profitability of agriculture and rendering it more volatile.

Table 6: Irrigation Costs Over Time (PKR/acre)

District	2010 Cost	2015 Cost	2020 Cost	2024 Cost
Multan	3200	4200	5200	6000

Bahawalpur	3400	4400	5400	6200
Dadu	3600	4600	5800	6700
Larkana	3500	4550	5650	6550

Figure 6: Irrigation Costs by District and Year



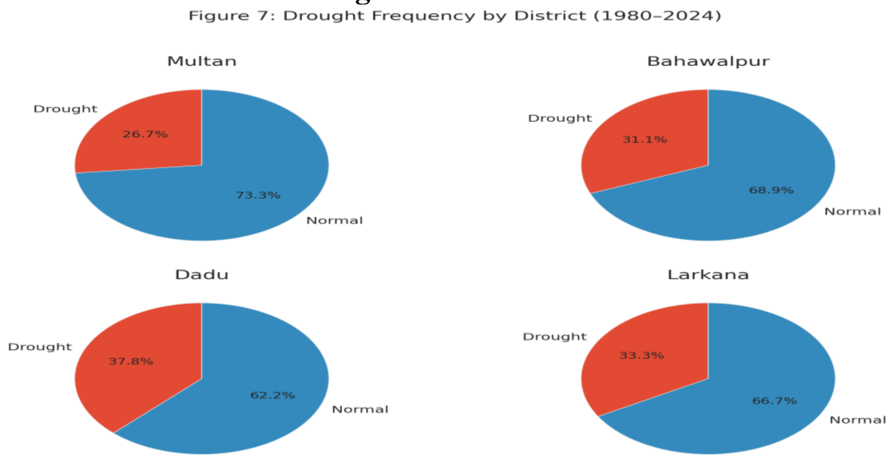
4.7 Increased Drought Frequency

Another impact of climate variability that has been reported is the increment in drought frequency which is evident in Table 7. The drought frequency in Dadu was 37.8 percent that is, 17 times a 45-year-long observation period, which is one of the top frequencies of droughts in the study districts. This information is shown in figure 7 which summarizes the number of drought years out of the total number of years as a pie chart in each district. These phases of long dry periods have direct effects of lowering access to water but they also affect cropping calendars, animal health, and income security in rural households.

Table 7: Drought Frequency by District (1980–2024)

District	Total Years Observed	Drought Years	Drought Frequency (%)
Multan	45	12	26.67
Bahawalpur	45	14	31.11
Dadu	45	17	37.78
Larkana	45	15	33.33

Figure 7 Larkana



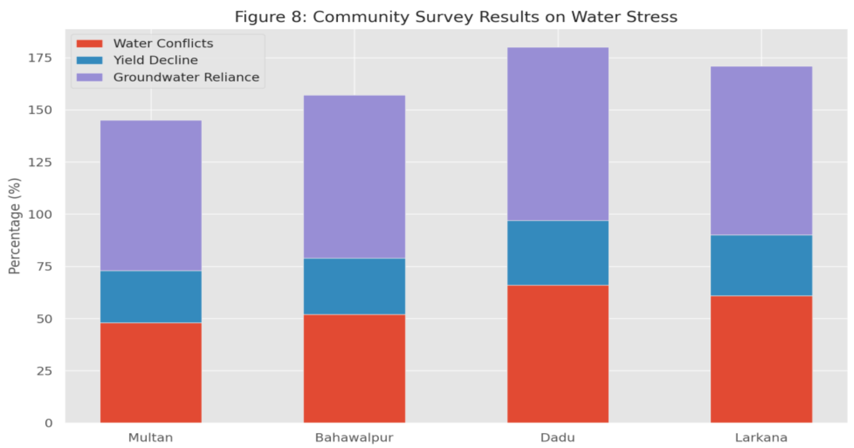
4.8 Community-Level Impacts and Perceptions

Structured surveys described the socio-economic impact of climate-mediated water stress (summarized in Table 8). The highest reported cases of water-related conflicts in Dadu and Larkana stood at 66 and 61 percent respectively, and groundwater dependency at 83 and 81 percent respectively. This has been shown in a stacked bar diagram in Figure 8 where the water conflict, perceived water yield reduction, and the reliance on groundwater can be discussed comprehensively. This evidence is clear in that higher hydrological stress is accompanied by greater social tension, livelihood vulnerability, and lower resilience to future climate shocks at higher levels of high hydrological stress.

Table 8: Survey Summary of Water Stress (2024)

District	Respondents Surveyed	Water Conflicts (%)	Yield Decline (%)	Groundwater Dependence (%)
Multan	80	48	25	72
Bahawalpur	76	52	27	78
Dadu	78	66	31	83
Larkana	78	61	29	81

Figure 8: Community Survey Results on Water Stress



5. Discussion

The evidence of the research proves the increasing influence of climate change on the water resources of the semi-arid areas of Pakistan which harbor tremendous indicating effects on the hydrological regimes, food production, and social stability. Such results complement the body of evidence across the world that demonstrates that arid and semi-arid environments are increasingly being impacted disproportionately by climate related hydrological variability (Kundzewicz et al., 2008; Schilling et al., 2012). The systematic trend of reduced rainfall and river outflow in both amount each year and volume as observed in this work is indicative of the overall regional tendencies in South Asia where the South Asian monsoon rain system has exhibited both spatial and temporal intensity losses even as global temperature has increased and ocean-atmosphere interactions have changed (Turner & Annamalai, 2012).

These findings are supported by the results of regional hydrological studies showing that Himalayan-fed rivers have been experiencing declining late-summer run-off as glacier retreat and snowpack loss reduce river discharge (Immerzeel et al., 2013; Lutz et al., 2014). It is particularly concerning that with dependence on the Indus River to provide more than 90 percent of Pakistan's irrigations (Wheater et al., 2010), things are getting worse. Also contributing to the situation, there is no natural water storage, and groundwater stocks are declining, which, in the past, compensated during dry seasons (MacDonald et al., 2016). The unsustainable rate of groundwater aquifers depletion that can no longer be replenished by natural rainfall recharge as demonstrated by the plummeting groundwater tables in other districts like Dadu and Larkana is evidence of this unsustainability in extraction rates.

The evidence provided in this study of water quality degradation especially in the form of high levels of nitrates and electrical conductivity makes the human health as well as agricultural sustainability alarming. Extreme amounts of nitrate in drinking water in the countryside in South Asia have been the direct result of poor sanitation, excessive fertilizer use, and a lack of regulatory control (Shamsudduha et al., 2011). Electrical conductivity of 2000 10S/cm in Dadu and Larkana reflects severe levels of salinization that may eventually make soils unproductive and affect crop productivity (Datta et al., 2009). Such results align with the situation in other semi-arid landscapes, including western India and portions of Iran, where secondary land degradation caused by increased salinity is beginning to decrease land productivity (Bazrkar et al., 2018; Singh & Kumar, 2019).

The direct effect of the hydrological stress on agriculture is supported by the observed decrease in the yields of wheat, cotton and rice. In sub-Saharan Africa, the Indo-Gangetic Plain, and other similar regimes, have observed in line that inconsistent irrigation, poor water quality, and higher heat wave occurrence are causing a 1030% reduction in major cereal production (Lobell et al., 2008; Aggarwal et al., 2019). Fall in Pakistan causes a ripple effect, because agriculture of the country constitutes a large percentage of employment and gross domestic product. The growing costs of irrigation that these farmers report in this paper match international findings that groundwater grows more costly to pump as water tables decline, further undermining profitability in the sector and forcing marginal farmers into debt (Giordano, 2009).

It is also extremely important to consider the social impacts of water stress due to the results of the community survey. The results indicate that conflicts among households have sharply increased, especially in the areas that are most exposed to drought and groundwater use. This is in line with the research by Wolf et al. (2003) whereby water scarcity was cited as a primary cause of intra community and inter community conflicts in the environmentally vulnerable regions. Caused by climate, competition in the ways people acquire resources tends to foster already existing inequality especially among the smallholder farmers and the marginalized communities, women being a part of it, since they have less control over decision-making and technology changes that are adaptive to the climate change (Ribot, 2010; Bose, 2011). In Pakistan, water disputes tend to be resolved informally or by tribal/customary mechanisms in rural areas, where they can be either non-binding in their dispute resolution and tend to discriminate in favor of established landowners.

Moreover, the growing rate and severity of droughts indicate the insufficiency of the existing early warning and drought preparedness systems. The meteorological and hydrological forecasting systems in Pakistan are disparate, and the local climate projections are not well incorporated into the water governance (Hassan et al., 2019). According to Arshad & Shakir (2021), the absence of real-time data and the coordination between institutions result in delayed reaction and uncoordinated relief measures. The drought statistics in this research require immediate investment in the modernization of meteorology and contingency planning at a district level, particularly in the most vulnerable areas such as Dadu and Bahawalpur.

Hydrological models such as SWAT employed in this research provide powerful scenario planning and water resource simulation tools under alternative climate futures. Nevertheless, their use is limited by the availability of data and the difficulties in modeling and calibration in developing nations (Tessendorf et al., 2020). The projections in this study are commensurate with the regional-scale model of climate change but the predictions would have been more reliable with finer-scale, terrestrial data. Such models can be further made useful in integrated water planning by adding socio-economic drivers and policy variables through models such as WEAP (Water Evaluation and Planning System) (Yates et al., 2005).

There are numerous implications of these findings. To start with, the data overwhelmingly indicate that an urgent change is required in groundwater policy. Although the National Water Policy (2018) recognizes the issue of over-extraction, monitoring and enforcement systems in the majority of provinces are either weak or non-existent (Raza et al., 2021). Second, to ensure water is used responsibly and to prevent wastage, water pricing and metering (which are contentious but unavoidable) initiatives should be subject to a pilot phase in partnership with the community. Third, subsidies and farmer training programs need to be increased to adopt climate-resilient crops and precision irrigation technologies such as drip and sprinkler systems (Zougmoré et al., 2018). Finally, institutional frameworks should be transformed and integrate climate risk in water governance and tempting cross-sectoral planning among agriculture, environment and disaster management departments.

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