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Impact of climate change on water scarcity in Pakistan. Implications for water management and policy

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ABSTRACT

Water resources in Pakistan are under serious threat from climate change (CC), exacerbating water scarcity. The implications for water policy and management are far-reaching. Pakistan relies heavily on the Indus Basin Irrigation System (IBIS) for agricultural production and water supply, but the distribution and availability of water resources are threatened by changing climatic patterns, such as changing precipitation and melting glaciers. Water scarcity is heightened by faster glacial melt and erratic precipitation patterns, which affect the timing and quantity of water flow. Effective water management techniques, such as increased effectiveness, sustainable practices, and conservation measures, as well as robust infrastructure and governance are required to address these issues. Pakistan can benefit greatly from international cooperation and assistance to mitigate the impacts of CC and ensure water security for long-term development.

Key words: climate change, Indus Basin Irrigation System (IBIS), management policy, sustainable development, water scarcity, water security

HIGHLIGHTS

- Urgent environmental concern.
- Policy and governance relevance.
- Climate change mitigation and adaptation.
- Community engagement and capacity building.

1. INTRODUCTION

Global climate change (CC) is mostly caused by human activity, specifically the atmospheric release of greenhouse gases (Mahmood *et al.* 2016). As a result, the Earth's surface is exposed to a number of risks, such as heat waves, tropical cyclones, droughts, and excessive precipitation (Haddad *et al.* 2020). These disasters have different impacts on different geographical areas, with negative social, economic, health, and environmental consequences. Interestingly, the health impacts are greatest in countries that contribute the least to greenhouse gas emissions (Ebi & Hess 2020).

Water security is one of the most significant effects of CC, which affects food security, agricultural productivity, food availability, and prices. These factors ultimately affect sustainable development, poverty, and inequality. To address these issues, water availability and use are critical, and it is becoming increasingly clear that everyone needs to become 'water conscious' and act quickly (Mendes *et al.* 2020). Pakistan faces strategic issues due to its particular weather patterns and increased vulnerability to the adverse effects of CC (Bacha *et al.* 2021). In recent years, severe flooding has occurred due to rising temperatures, which have led to record rainfall and rapid melting of glaciers in the northern regions (Guterres 2022). Due to these climate-related events, food shortages, water crises, and significant impacts on human security are expected in Pakistan (Tan 2022). Figure 1 shows how the available water in Pakistan is used by the sector.

Pakistan currently has the third highest water scarcity in the world and is the country most affected by CC (Basharat 2019). Pakistan's water scarcity is mainly caused by pollution, low rainfall, drought, and inadequate management. Pakistan's water resources are under extreme strain due to its growing population, which is largely dependent on agriculture to drive the country's export earnings, employment, and GDP (Yaqoob *et al.* 2021).

The availability of surface water in Pakistan has drastically decreased over time, leading to water scarcity, and future estimates indicate even greater losses (Janjua *et al.* 2021). CC, which is defined by rising temperatures and shifting rainfall

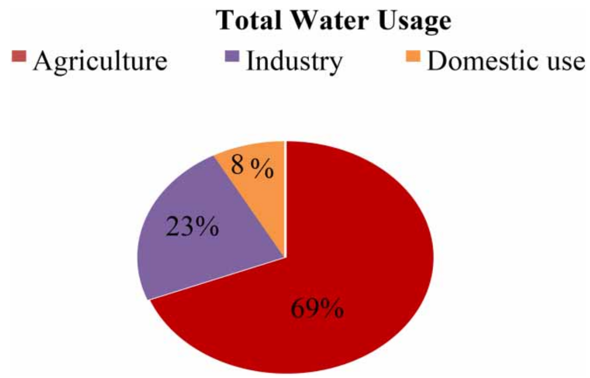

Figure 1 | Pakistan's water usage distribution by sector (Ishaque *et al.* 2022).

patterns, is a significant factor affecting the nation's water supplies (Stocker 2014). Taking into account, the changes in soil, water, and vegetation, modeling methods such as the Soil and Water Assessment Tool (SWAT) have been used to assess the potential impacts of CC on water supply (Maraun *et al.* 2010). Given the severity of the water crisis, the Pakistani government has declared a state of emergency (Syed *et al.* 2021). Global warming and imbalances in the hydrological system are largely caused by human actions such as the burning of fossil fuels, changing land uses, and deforestation exacerbating the result of CC on water supply (Mahmood & Babel 2013). As the hydrological cycle of a catchment is influenced by both physical characteristics and climatic factors, effective water resources management must take CC into account (Wang *et al.* 2012).

Several complex causes such as population growth, CC, inadequate water management techniques, and social and political difficulties all have an impact on the problem of water scarcity. The growing gap between demand and water availability in Pakistan is due to a number of factors, including population growth, rapid urbanization, and inadequate water management techniques (Mahmood & Babel 2013). To solve these problems, new information, methods, and technologies need to be developed that consider the economic, social, political, and environmental elements of managing water resources (Shrestha *et al.* 2016). The study aims to investigate water scarcity in different locations, evaluate the effectiveness of current water management strategies and policies, and assess the current and projected impacts of CC on Pakistan's water resources. Pakistan faces interrelated concerns such as water scarcity and CC, which need for integrated approaches. It is essential to comprehend how these problems relate to one another and the elements that contribute to them. Water scarcity is made worse by CC, which also modifies water resources and throws off weather patterns. Effectively managing the consequences of climate change on water resources requires a comprehensive approach encompassing water conservation, infrastructure resilience, alternative supply development, and enhanced resource governance. The objective of this study is to suggest options for adaptation and mitigation that will improve water security and foster sustainable economic growth in Pakistan. Policymakers can create comprehensive policies that mitigate the negative effects of CC on water resources by taking into account the connections between water shortage, CC, and efficient water management.

2. PAKISTAN'S WATER SCARCITY AND ENVIRONMENTAL SUSTAINABILITY

Pakistan's serious problem of water scarcity and how it relates to many other factors. The seriousness of the problem is exhibited by Pakistan's third place ranking among nations with low water resources, as reported by the IMF (Verbeek & Osorio Rodarte 2015). According to a study by the Council of Research in Water Resources (PCRWR) and the Pakistan Academy of Science, a serious water deficit is expected in Pakistan by 2025. The literature also describes the historical vulnerability of the Indus basin to droughts (Zhang & Gao 2020). Increasing water demand in Pakistan is a result of heavy reliance on agriculture, population growth, and urban planning, but it remains impossible to predict supply (Aijaz & Akhter 2020). The country finite and unsustainable water supply is a serious challenge, exacerbated by increasing pollution and CC (Zhang *et al.* 2020). Heat waves, floods, and droughts are examples of climate that exacerbating food insecurity and having a disproportionate impact on impoverished populations, as a large proportion of the population relies on agriculture and natural resources for their livelihoods (Jamil 2019). Apart from the depletion of natural resources, water scarcity in Pakistan contributes to a number of socio-economic challenges, a lack of food access, a rise in the need for clean water, and health issues. Access to water has a significant impact on many areas of public and private life and is an essential prerequisite for economic growth. The strain on already limited water supplies is heightened by the inability to conserve water and manage wastewater. With fewer than a thousand cubic meters of water annually per person, Pakistan is considered a water-scarce nation. By 2025, the country would suffer from complete water scarcity if the current situation continues and per capita water consumption reaches 500 cubic meters (Fahad & Wang 2020). Access to clean water is a serious problem, as 80% of people in large cities have no access. This is most evident in Karachi, where over 16 million people are affected (Kummu *et al.* 2016). Unforeseen meteorological conditions, such as changing monsoon patterns and melting glaciers, affect major rivers such as the Indus, causing reservoirs such as Tarbela and Mangla to lose capacity. Unexpected floods and droughts are the result, endangering lives, upsetting families, and uprooting vulnerable communities (Zhang *et al.* 2020). For poor communities, increased competition for water resources and worsening food shortages caused by CC pose life-threatening challenges. Indicators such as the Water Resources Vulnerability Index, the Falkenmark Indicator, the IWMI Physical and Economic Water Shortage Indicators, and the Water Poverty Index can be used to determine the extent of water scarcity (Chakkaravarthy & Balakrishnan 2019). A relationship between population and water availability, with countries with water scarcity is having a per capita water resource of less than 1,700 m^3 per person (Figure 2). A country is considered water scarce if water availability per person is less than 1,000 m^3, and the absolute amount of water scarceness is less than 500 m^3 per person. Pakistan is projected to approach the threshold of absolute water scarcity by 2025 if the current trend continues, having already crossed the water stress threshold in 1990 and the water scarcity threshold in 2005 (Ishaque *et al.* 2022).

2.1. Impact of CC on freshwater security

To understand this problem, you need to know how water is distributed on Earth, where only 2% of the water is fresh and 98% of the water is salty. About 70% of this, 2% is frozen as snow and ice, 30% is groundwater, and less than 5% is surface water from rivers and lakes. The proportion of freshwater in the atmosphere is also very low at less than 0.05% (Molle *et al.* 2009). CC has a major impact on these conditions, especially when it comes to the melting of polar ice, which converts freshwater into salt water and affects the overall freshwater supply (de Bruin *et al.* 2018).

Both inadequate water supply infrastructure and water quality impairments can affect the availability of freshwater. According to the International Convention to Combat Desertification (Reynolds *et al.* 2007), CC and human activities are degrading soil quality and transforming productive land into arid, semi-arid, and sub-humid regions. Water supply is further affected by CC as it leads to increased evapotranspiration, altered precipitation patterns, and the drying up of rivers and lakes, especially in areas with permafrost. CC also affects water quality by promoting the growth of pollutants through erosion, turbidity, and flooding.

There is also a great need for water due to rising demand worldwide for food and energy, which is expected to rise by 50% by 2030 (Karp & Richter 2011). Water scarcity, in whatever form, therefore has a major effect on both people and the environment. The increase in water in the atmosphere due to rising temperatures leads to increased precipitation; however, the ability of water to be stored and used is impaired by the rapid return of air to the oceans (Haseen *et al.* 2012). Increased evaporation from warmer air leads to rainfall replacing snowfall. In the case of freshwater resources, there is a short-term

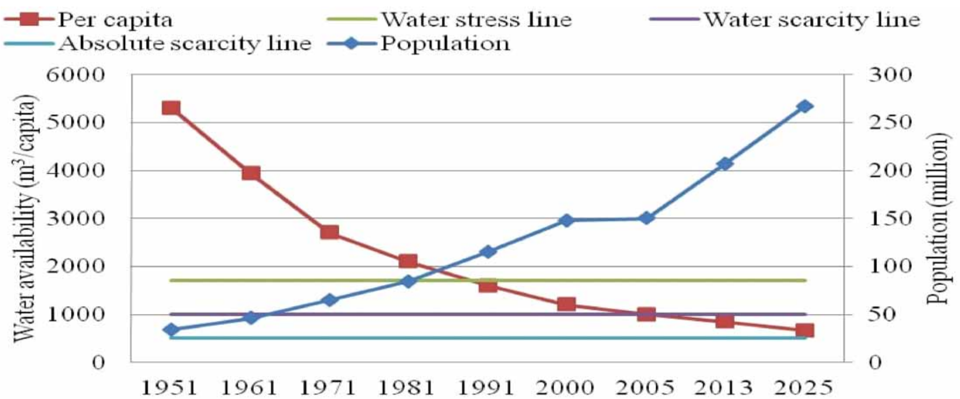

Figure 2 | Water availability in Pakistan by 2025 taken from Dr Muhammad Ashraf's research report.

increase in water availability due to glacier melt. Precipitation in semi-arid regions has decreased due to CC. Severe droughts and massive flooding are being caused worldwide by the intensification of the water cycle as a result of CC.

According to a recent analysis by the United Nations Environment Programmed, freshwater scarcity caused by CC is not the only problem, but triggers a series of interconnected problems. Growing demand in agriculture due to population growth is consuming excessive amounts of water for irrigation, which is polluting the water supply. Pakistan is one of the many countries whose water-intensive lifestyles exacerbate the problem. Even in developing countries with rapidly expanding industries, the lack of modern technology means that pollution management and water conservation are often neglected (Molle *et al.* 2009). Therefore, tackling water demand and pollution must go hand in hand with tackling CC.

2.2. Understanding Pakistan's reaction to CC

Environmental problems such as ozone depletion and CC are interrelated. Global warming is a result of greenhouse gas emissions, which are the main cause of CC (Bowen & Ebi 2015). Changes in atmospheric circulation patterns brought about by global warming might affect the location and intensity of ozone thinning, particularly in polar areas. However, the release of ozone-depleting chemicals like chlorofluorocarbons (CFCs) is what causes ozone depletion (McDermott-Levy *et al.* 2019). The usage of these compounds has been successfully decreased by the Montreal Protocol, and the ozone layer is recovering. Recent research, however, has refuted the idea of a new, bigger ozone hole in the tropics, highlighting the significance of resolving the well-established ozone hole in the Antarctic (Fang *et al.* 2019). The problems faced by industrialized nations and the thinning ozone layer are made worse by a lack of concern and insufficient action on CC (Wardekker *et al.* 2012). In addition to contributing to ozone depletion, rising global temperatures also have a domino impact on other environmental factors. Increased UV radiation brought on by ozone depletion has a detrimental impact on human health, notably the immune system and cancer risk. It also has an effect on agriculture, lowering agricultural production (Wardekker *et al.* 2012). Human activity is the common factor between ozone depletion and CC (Kumar *et al.* 2021). In addition to acting as greenhouse gases and destroying the ozone layer, substances like CFCs also contribute to global warming (Roy 2020). There is a complicated link between these two problems. There is a slight cooling effect of ozone depletion in the stratosphere, but future ozone levels may be impacted by CC (Barnes *et al.* 2019). Positive effects have been seen in the efforts to phase out ozone-depleting compounds, and the ozone layer is expected to rebound (Roy 2020) (Figure 3).

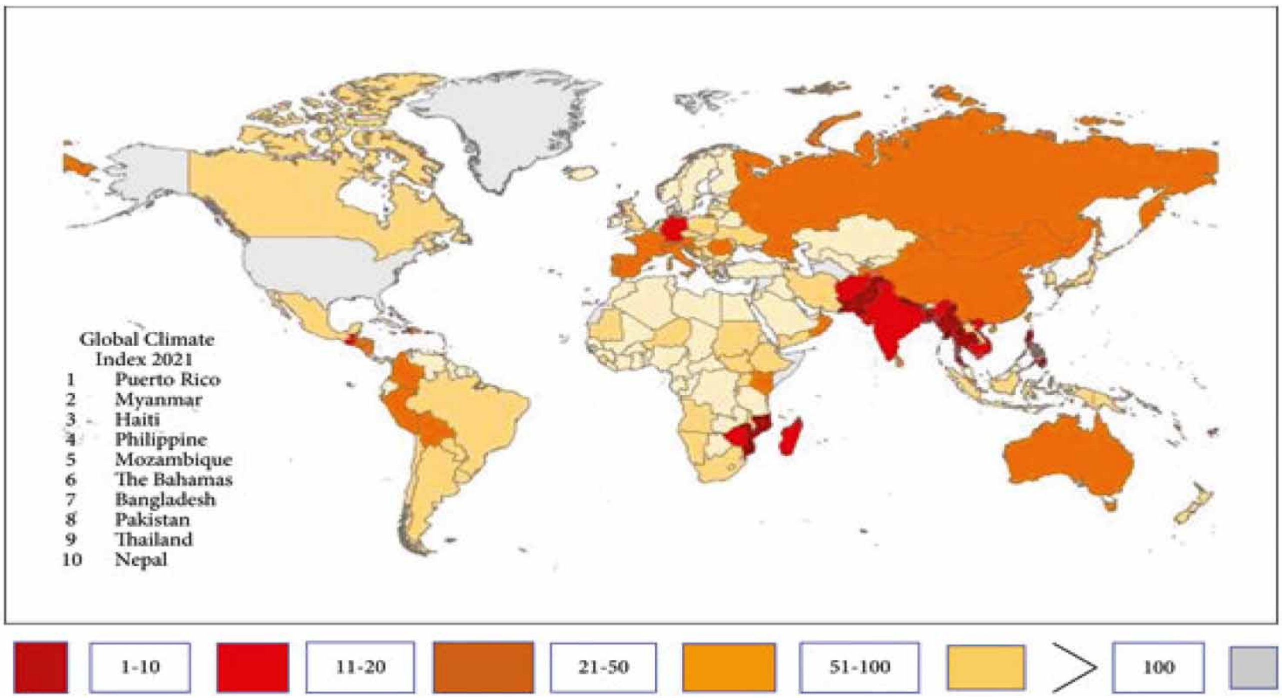

Figure 3 | Pakistan susceptibility and the climate risk index (Akbar *et al.* 2021).

The Paris Agreement, the Copenhagen Accord, and the Kyoto Protocol are just a few of the accords and efforts that have been sparked by the United Nations Framework Convention on Climate Change (UNFCCC). The industrialized nations that release the most carbon dioxide and other greenhouse gases into the atmosphere, however, were free to leave these agreements if they did not serve their economic interests because of the global order's sovereign status, which made them non-binding. Figure 4 presents a ranking of the top 10 most polluted countries worldwide in 2020. In 2022, China continues to lead the world in CO_2 emissions, followed by the US in second place with 4.4 billion tons and India in third place with 2.3 billion tons.

Figure 5 shows that although the countries mentioned are not among the 10 largest CO_2 emitters worldwide due to their heavy dependence on oil and their small populations, they are among the 10 largest per capita emitters. On 9 and 10 September 2022, Antonio Gutters, the Secretary-General of the United Nations, visited Pakistan in an official capacity to offer support to the victims of the flood crisis and to evaluate the destruction by means of official briefings and field trips. Pakistan generates less than 1% of global emissions, yet he says the elements have destroyed Pakistan (Ishaque *et al.* 2022). Additionally, he said, 'It was outrageous that action to reduce greenhouse gas emissions was being put on the back burner because tomorrow it could be your country, and today it was Pakistan' (Guterres 2022a, 2022b), referring to industrialized nations. Pakistan is ranked 8th in the vulnerability index of the Global Climate Index (GCI) 2021, further confirming the country's vulnerability to climate risks. The analysis demonstrates the serious effects of CC on Pakistan, from severe heat and drought to disastrous food shortages (Ishaque *et al.* 2022) (Table 1).

2.3. An examination of Pakistan's quality of drinking water

In Pakistan, the quality of the accessible drinking water is appalling. In both large cities and rural locations, there are contaminated and disease-prone surface and underground water sources (Mahmood & Babel 2013). Overall, Pakistan is classified as a 'water stressed' nation and is rapidly approaching the status of a 'water-scarce' nation in the next few years due to the sharp decline in the amount of water available per person (Chu *et al.* 2010). The changing circumstances also make it more difficult to obtain water for everyday needs and agricultural output, which exacerbates Pakistan's problems with human security (Solomon 2007). The most often used term in Pakistan these days is 'water pollution', which has many different causes that affect the quality of the water that is readily available (Khattak *et al.* 2011). An increase in air temperatures, which has the innate ability to raise the temperature of drinking water, microorganisms, organic compounds, nutrients, and heavy metals, is one of the common causes (Zhang *et al.* 2011).

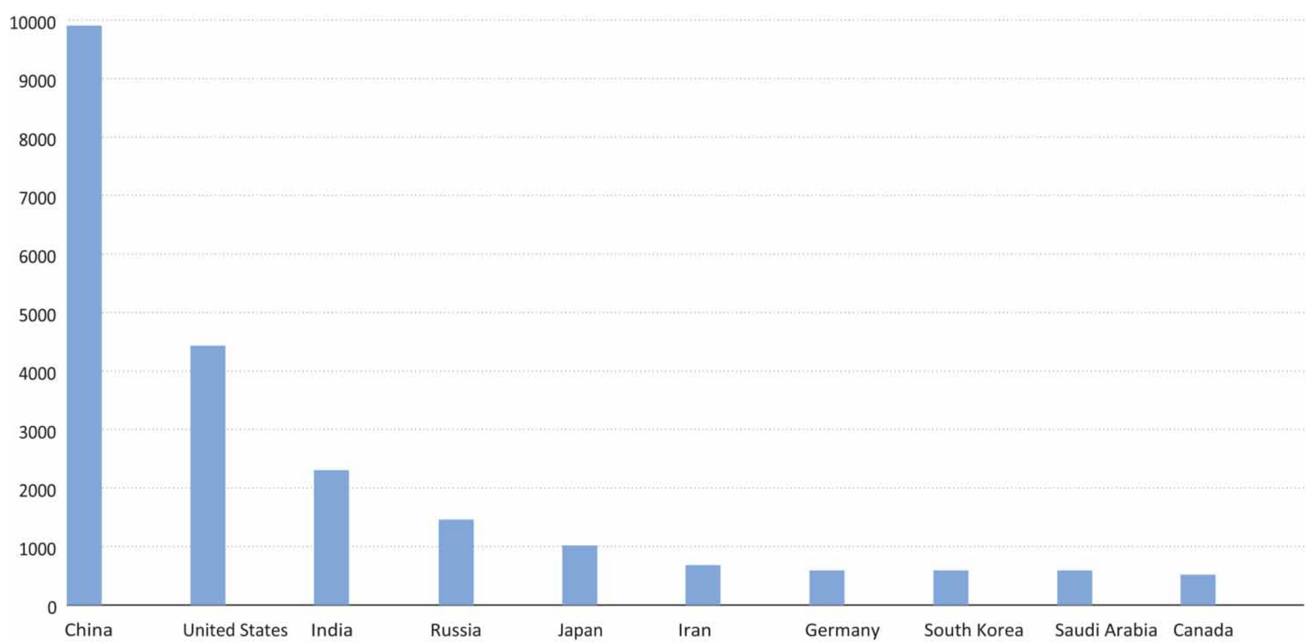

Figure 4 | 2020 top 10 most polluted countries (in million tonnes of CO_2) (Garrett 2021).

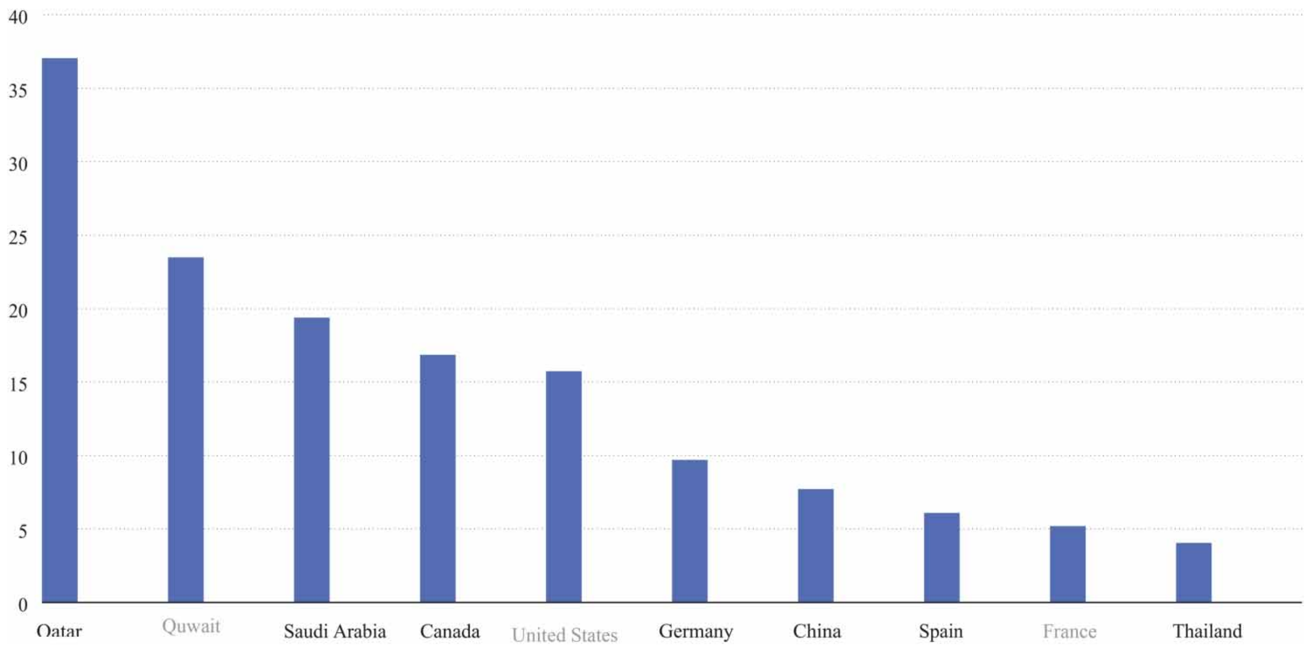

Figure 5 | 2022 top 10 polluting nations per capita (Garrett 2021).

Table 1 | Global Climate Index 2021 (Eckstein *et al.* 2021; Ishaque *et al.* 2022)

Cri 2000–2019 (1999–2018)	Country	Cri score	Fatalities	Fatalities per 100,000 inhabitants	Losses in millions US$ PPP	Losses per unit GDP in %	Number of events 2000–2019
1 (1)	Puerto Rico	7.17	149.85	4.12	4,149.98	3.66	24
2 (2)	Myanmar	10.00	7,056.45	14.35	1,512.11	0.80	57
3 (3)	Haiti	13.67	274.05	2.78	392.54	2.30	80
4 (4)	Philippine	18.17	859.35	0.93	3,179.12	0.54	317
5 (14)	Mozambique	25.83	125.40	0.52	303.03	1.33	57
6 (20)	The Bahamas	27.67	5.35	1.56	426.88	3.88	13
7 (7)	Bangladesh	28.33	572.50	0.38	1,860.04	0.41	185
8 (5)	Pakistan	29.00	502.45	0.30	3,771.91	0.52	173
9 (8)	Thailand	29.83	137.75	0.21	7,719.15	0.82	146
10 (9)	Nepal	31.33	217.15	0.82	233.06	0.39	191

The Drinking Water Quality Monitoring Program results from 24 of Pakistan's biggest cities are displayed (2002–2020). According to the survey, over 80% of the sample was considered unfit for human consumption (Table 2).

2.4. Analysis of Pakistan's water disasters

Pakistan's ever-changing climate and topography present serious issues when it comes to water-related disasters. CC makes extreme weather events like heatwaves, cold snaps, and torrential rainstorms more common in the nation. The highest temperature ever recorded in Pakistan's history was 53.7 °C on 28 May 2017, in Turbat, Baluchistan, and the second highest temperature was 53.5 °C on 26 May 2010, in Moenjo Daro, Sindh. These extremely high temperatures are among the hottest that have ever been recorded worldwide (Johnson & Manikandan 2023; Zahra *et al.* 2023).

The impact of CC on water supply in the Indus basin, which is highly susceptible to glacial melt and changing precipitation patterns, is difficult to predict. Approximately 45% of the water flow to the basin comes from the melting of snow and glaciers

Table 2 | Water quality Pakistan Council of Research in Water Resources (pcrwr.gov.pk)

Province	Districts surveyed	Water supply schemes reported by provinces	Surveyed water supply schemes			Functional	Samples safe for drinking (%age)	
			Total	Urban	Rural		Urban	Rural
Punjab	33	4,100	3,850	713	3,137	2,698	17	23
Sindh	22	1,300	1,247	123	1,124	529	5	5
KPK	16	3,000	2,203	474	1,729	1,710	63	26
Baluchistan	14	1,600	1,034	480	554	968	20	13
GB/AJK/FATA	10	2,000	1,794	18	1,776	1,379	8	2
Total	95	12,000	10,128	1,808	8,320	7,284	23	14

in the Himalayas. The acceleration of glacier retreat is evident from the disappearance of local glaciers, aligning with global trends. It is predicted that glacier melt, driven by rising global temperatures, will further increase river flow by 40% in the coming years. However, over time, the normal flows of the Indus River are expected to drop by more than 60% (Lau & Kim 2012; Dhaubanjar *et al.* 2021; Yaqoob *et al.* 2021). The unequal distribution of water and decreasing water availability have led to tensions among various provinces in Pakistan. CC and variability are anticipated to impact the quantity and quality of irrigation and hydropower output, further exacerbating tensions, particularly in downstream provinces like Sindh. To address these challenges, it is crucial to develop, operate, and maintain hydrological infrastructure with a clear estimation of future water supplies under changing climatic conditions (Jetly 2012; Connor 2015; Ahmed *et al.* 2016). Furthermore, Pakistan's neighbors, Afghanistan and India, also share water resources. There is no agreement between Pakistan and Afghanistan on the Kabul River, an important resource along the Indus River system, despite the fact that Pakistan and India signed a large water deal in 1960 that included sharing the Indus, Chenab, Jhelum, Beas, Ravi, and Sutlej rivers. Over 20 million people depend on the Kabul basin for their water supply, making them especially susceptible to the effects of CC. As riparian nations, Pakistan and Afghanistan are vulnerable to the effects of CC and its possible ramifications for the entire area (Jamil 2019). Pakistan's changing climate, characterized by more frequent heatwaves, floods, and droughts, worsens the country's food insecurity problem. The lives and livelihoods of underprivileged and impoverished groups, who heavily rely on farming and natural resources, are greatly impacted by these shifting climate conditions. CC, population growth, and extensive urbanization pose escalating challenges in accessing water and food, which can determine the survival of individuals living in poverty (Verbeek & Osorio Rodarte 2015).

When comparing the annual water availability with the total annual drawls, Pakistan comes in third place among the countries with limited water resources. According to a report from the Council of Research in Water Resources (PCRWR) and the Pakistan Academy of Science, it is expected to have a severe water scarcity by 2025. The Indus basin has seen frequent droughts since the 19th century, and the country's finite and sustainable water supply is being seriously threatened by rising pollution levels and CC. Water security must be addressed immediately in order to lessen the sufferings and injustices that socially vulnerable communities must endure (Qureshi & Ashraf 2019; Zhang *et al.* 2020).

2.5. Impact of CC on Pakistan's economy and agriculture

CC puts Pakistan's food security in grave jeopardy. According to German Watch, a German research tank, Pakistan was one of the top 10 nations afflicted by climate-related disasters in the last 20 years (Weischer *et al.* 2016). The country's already fragile agro-based economy is under additional stress from the financial losses brought on by CC (Arshad & Shafi 2010). Approximately 20% of Pakistan's GDP comes from agriculture, which is negatively impacted by CC (Arshad & Shafi 2010). Indicators of CC in Pakistan include changes in rainfall patterns, rising temperatures, droughts, floods, and glacial retreats (Safdar *et al.* 2019). By 2050, Pakistan is projected to have a population of 350 million. To meet their food demands, the nation will need to produce 10 million tons (MT) of rice and 40 MT of wheat (Kugelman & Hathaway 2010). The yield of major crops could decline by 6–16% due to CC (Akbar & Gheewala 2020). 93% of Pakistan's water resources are employed by the agricultural sector, making water a crucial component of agriculture (Qureshi 2019). Food insecurity is a result of ineffective water management, a lack of conservation efforts, and inefficient water use (Raza *et al.* 2012; Parry 2016). Water infrastructure across the nation has to be realigned (Memon & Thapa 2011). Glacial retreat will produce more water as a result of rising temperatures, and the current infrastructure may not be sufficient to store this water (Laghari *et al.* 2012). By 2030, Pakistan's per-person water availability could be less than 1,000 m^3 water scarcity (Hassan *et al.* 2019).

3. PAKISTAN'S WATER RESOURCES

3.1. Rainfall

The monsoon is Pakistan's primary source of precipitation (July–September) and the eastern downswings (December–March). During most of the Kharif and Rabi seasons, the entire Indus plains receive an average of 212 and 53 mm of rainfall, respectively (Naseer 2013; Khana *et al.* 2020). Figure 6 shows the average rainfall statistics for some major cities based on a 10-year median (1996–2006).

3.2. Glaciers

Glaciers cover over 13,680 km^2 of Pakistan's total area, which contributes to increased river runoff during warm weather. It is estimated that the glaciers in the Himalayas have shrunk by almost a fifth in just 30 years and will disappear completely by 2035, with catastrophic consequences for the 1.3 billion people living in the river basins downstream that supply them with food and energy (Naseer 2013).

3.3. Dams and rivers

Pakistan has given the Indus a large number of rivers, including the Jhelum, the Chenab, the Ravi, the Beas, and the Sutlej, the five main rivers that originate on the eastern side of the Indus, as well as the three smaller rivers Haro, Soan, and Siran (Hussain 2020).

3.4. The Indus River system

Pakistan's largest river and its most important waterway is the Indus, which was formed either by the Karakoram or Hindu Kush glaciers. It supplies water for household and commercial use and is necessary for over 90% of agriculture. The Jhelum, Ravi, Chenab, and Sutlej are additional areas of the Indus in its eastern portions (Clift *et al.* 2002). Under the Indus Water Treaty of 1960, Chenab, Jhelum, and Indus were handed over to Pakistan while India retained sovereignty over Bias, Ravi, and Sutlej (Salam *et al.* 2020). In addition, Pakistan has a number of smaller rivers that flow into the Indus in the west, the largest of which is the Kabul. Generally, rivers such as the Swat, Tochi, Gomal, and Kurram are involved (Cheema *et al.* 2014; Afzaal *et al.* 2019) (Table 3).

3.5. Hydropower

Pakistan has a hydroelectric capacity of roughly 40,000 MW in the upper Indus basin. Pakistan can now generate 22,797 MW of electricity. The shortfall is between 4,000 and 5,000 MW, while the total production is 17,000 MW. The most important energy sources are nuclear power and exports (5.8%) as well as crude oil (35.2%), hydrogen (29.9%), and gas (29%). Pakistan Water and Power developement Authority (WAPDA) forecasts a capacity of 75,149 MW by 2025, which can only be achieved through the construction of larger storage reservoirs (dams). Table 4 shows the thermal energy channels, trade, and energy generation in Pakistan (Afzal *et al.* 2017).

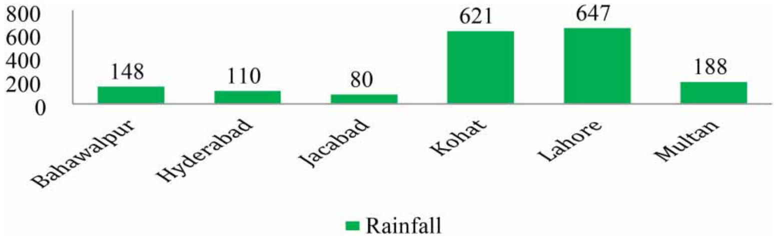

Figure 6 | Data on major cities' average rainfall over a 10-year period (1996–2006) (Khoso *et al.* 2015).

Table 3 | Annual average flow of water (BCM) (Khoso *et al.* 2015)

Sr. no.	River name	Crops Kharif	Rabi
1	Indus	61.71	12.30
2	Jhelum	20.28	8.35
3	Chenab	26.37	7.805
4	Ravi	1.433	0.435
5	Kabul	0.086	0.099
6	Sutlej	17.73	7.032
	Total	**127.609**	**36.021**

Table 4 | List of thermal stations in operation that have the ability to produce energy (Khoso *et al.* 2015)

Sr. no.	Thermal stations with operational fuel type	Location	Potential energy (MW)
1	Hub Power Company Plant (Thermal gas station fired with oil)	Hub Baluchistan	1,292
2	Hub Power Project Narowal (Furnace oil plant fired)	Narowal Punjab	225
3	Bin Qasim Power Plant (Plant fired with oil and natural gas)	Karachi, Sindh	1,260
4	Jamshoro Power Station (Plant fired with oil and natural gas)	Jamshoro, Sindh	1,054
5	Lalpir Limited (Thermal gas station fired with oil)	Muzaffargarh, Punjab	362
6	Altern Energy Limited (Diesel engine started with gas)	Fateh Jang, Punjab	29
7	Atlas Power Limited (Plant fired with oil furnace)	Sheikhupura, Punjab	225
8	Attock Gen Limited (Plant fired with oil furnace)	Rawalpindi, Punjab	165
9	Fauji Kabirwala Company (Paired cycled plant fired with gas)	KabirWala, Punjab	157
10	Gul Ahmed Energy Limited (Plant fired with oil furnace)	Karachi, Sindh	136
11	Nishat Power Limited (Plant fired with oil furnace)	Lahore, Punjab	200
12	Nishat Chunian Limited (Plant fired with oil furnace)	Lahore, Punjab	200
13	Sapphire Electric Company (Plant fired with oil furnace)	Muridke, Punjab	225
14	Saba Farooq Company (Plant fired with oil furnace)	Farooqabad, Punjab	125
15	Southern Electric Power Company (Plant fired with oil furnace)	Raiwind, Lahore	135
16	Tapal Energy Limited (Plant fired with oil furnace)	Karachi, Sindh	126
17	Japan Power Generation Limited (Plant fired with oil furnace)	Raiwind, Lahore	135
18	Kohinoor Energy Limited (Plant fired with oil furnace)	Lahore, Punjab	131
19	Sitara Energy Limited (Plant fired with diesel and natural gas)	Faisalabad, Punjab	85
20	Saif Power Limited (Plant fired with diesel and natural gas)	Sahiwal, Punjab	225

4. PAKISTAN'S SCARCITY CAUSES

4.1. Changes in Pakistan's climate

The current circumstances have also been impacted by CC. The water situation has gotten worse due to the extreme heat, melting glaciers, and methane releases. Because of harsh weather, rivers and seas are getting wetter every year. Only 65 individuals died of heatstroke in Karachi in May 2018. However, in 2015, extreme heat claimed the lives of approximately 1,200 people (Baloch 2018). Because of the intense heat and difficult terrain, the area frequently lacks water, which raises the possibility that it could someday turn into a searing desert. In addition, the monsoon season has become harder for meteorologists to anticipate in recent years due to its increased unpredictability. The winter and monsoon seasons have become shorter as a result of CC, lasting less time each year. The winter season, which used to last around 4 months, is now only about 2 months in many sections of the nation. Social changes exacerbate the impact of high heat and greenhouse gas emissions (Meribole 2020). The study emphasizes the importance of improving direct air capture technology cheaply and lowering energy costs in order to address CC through the mitigation of greenhouse gas emissions. The study assesses different strategies for halting global warming and investigates the possibilities of carbon capture technology. It implies that lowering greenhouse gas emissions and decreasing the effects of CC may be possible with direct air capture. For efficient carbon sequestration, the optimization of capture arrangements and the lowering of energy requirements are stressed. The costs and difficulties of using carbon capture techniques like post-combustion capture and oxy-fuel combustion are also acknowledged in the research. It comes to the conclusion that capital funding and specific plant designs are required for the effective application of carbon capture technologies (Towoju & Petinrin 2023). Pakistan's glaciers, in particular the Ultar Glacier, which has historically given local residents access to clean water and supported agricultural operations, show the negative consequences of environmental pollution and global warming (Ortas 2023). However, due to glacier melting, heavy rainfall (Figure 7), and hilly terrain, devastating floods are destroying a large number of houses and crops around the country. This results in water waste.

4.2. Reservoir slurry

The country has been compelled to save billions of dollars due to increasing power outages and water shortages. However, no one has addressed the erosion of the reservoirs' topsoil, which threatens the longevity of the dam and is the water source that has a major impact on agricultural output. Power and water shortages can be just as dangerous as siltation, if not more so (Hussain *et al.* 2020). Pakistan's largest reservoirs, Tarbela and Mangla, are at serious risk due to up to 8.126 billion cubic meters (BCM) of topsoil erosion over a 36-year period. This is a little worrying. Growing amounts of sand in the reservoirs have a negative impact on the age of recharge created under the Indus Waters Treaty (Mahdi *et al.* 2005). Refilling is urgently required under the Indus Water Treaty, as the treatment capacity is lost due to the topsoil erosion that occurs underneath. Topsoil erosion destroys aquifers, which also has a negative impact on the production of agricultural goods that require the construction of dams and the storage of water (Qureshi *et al.* 2008; Cech 2018). Similarly, flood control gates like slurry gates are essential for saving lives and property valued at trillions of dollars, as well as for keeping water available for farming.

The total loss due to erosion of the topsoil in the reservoirs amounts to about 16.258 BCM. The major reservoirs of Pakistan and their capacity for oil storage are listed in Table 5. The process by which water flows from the surface, edges of watercourses, and canals into the ground is called seepage. Although seepage losses in Pakistan are often substantial, they amount to only 8–10 cusecs per million square feet of wet cross-chapter area, or 35–40% of the flow into the canal. Pakistan's waterways and canals have a combined length of 56,073 km and 1.6 million km, respectively. Studies have shown that 18.3 million cubic meters of usable rainfall are lost annually through the tributaries in Pakistan's insignificant canals and rivers alone. This enormous waste of resources could be prevented so that 3.0 million hectares more land could be replanted

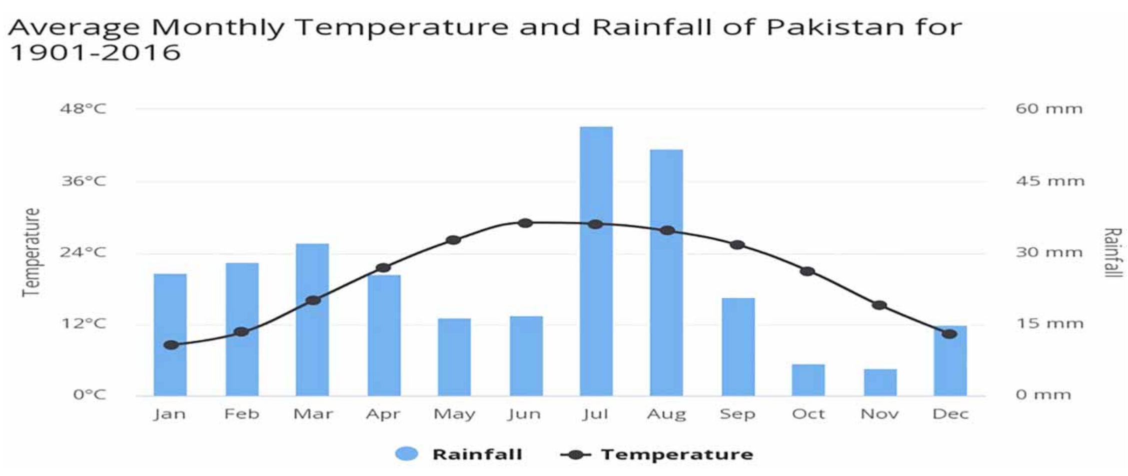

Figure 7 | Average monthly temperature and rainfall of Pakistan for 1901–2016 (Ortas 2023).

Table 5 | A list of the main reservoirs in Pakistan together with their capacity for storing (Khoso *et al.* 2015)

Sr. no.	Pakistan's major reservoir	Total storage capacity (BCM)
1	Tarbela Dam	12.575
2	Mangla Dam	6.911
3	Hub Dam	0.114
4	Tanda Dam	0.097
5	Khanpur Dam	0.073
6	Warsak Dam	0.0475
7	Rawal Dam	0.0475

each year. Pakistan's most important source of irrigation is the Indus (Hussain *et al.* 2020). The region can be further expanded if we reduce the losses from navigable waterways and canals. It is estimated that the major and minor distributaries and canals lose about 25% of the water (32.021 BCM). In addition, around 55.508 BCM of water is lost through flow, evaporation, transpiration, and flooding.

4.3. Increase in population

Pakistan's ongoing water crisis is also a result of population growth. It is the sixth largest country in the world, with nearly 220 million people. This region uses more water than nations like Saudi Arabia and the United Arab Emirates do. Given Pakistan's expanding population, a potential water catastrophe is even more plausible. As the population grows, the need for water increases. People from rural areas frequently relocate to urban areas in search of better educational and employment opportunities, and better quality of life due to the higher amenities that cities have to offer. After stocking up on the supplies they will need for the upcoming season, several of them return to their homes. Owing to migration and population increase, water availability has also started to decline over time. As more people move to urban regions and large cities, more water is required. It could be difficult to use the water supply because many people dwell in one building, particularly in apartments.

4.4. Inadequate water storage

Inadequate storage is one of the main causes of water scarcity. Pakistan has far less water storage per person than other nations do. Australia and the USA have per-person water storage of nearly 5,000 m^3, China 2,200 m^3, Egypt 2,362 m^3, Turkey 1,402 m^3, and Iran 492 m^3, but Pakistan has only 159 m^3. Aswan High Dam on the Nile River has a storage capacity of roughly 1,000 days, compared with 900 days for the Colorado and Murray-Darling rivers, 500 days for the Orange River in South Africa, 320 days for India, and barely 30 days for Pakistan (Connor 2015). In addition to having catastrophic effects on infrastructure, agriculture, livestock, and people, Pakistan lost more than 120 BCM of water during the floods of 2010, 2012, and 2014 because of inadequate storage. However, Pakistan Vision 2025 set a goal of 90 days of storage by that year. In contrast to the global average of 40%, the current water storage capacity of the three large reservoirs is only 9% of the average annual inflow. The capacity of the reservoirs is depleted at a rate of 0.27 BCM annually because of sedimentation. About 8.1 BCM of the reservoirs' storage capacity was lost by 2010 (Qureshi & Ashraf 2019).

4.5. Low system efficiency

The overall efficiency of the irrigation system is less than 40%, owing to aging and poor maintenance. For instance, only approximately 55 BCM of 143 BCM of water available at the canal head work is used by crops (Commission 2008). During transportation through canals, distributaries, minors, and watercourses as well as during application in the fields, the remaining 87 BCM (61%) were lost. As it can be pumped back when necessary, the water lost by seepage in regions where fresh groundwater is present is only a temporary loss. However, because this water must be pumped, there is energy loss. This is a permanent loss in regions where saline groundwater is present, because it cannot be used for drinking or irrigation and may cause water logging and salinity (Ullah *et al.* 2018).

4.6. Water logging and salinity

Agriculture faces a major threat from salinity and waterlogging. Only 16.4 MT of the 33 MT of salts that enter the Indus Basin Irrigation System (IBIS) flow to the sea. Only 2.2 MT of the 16.6 MT of salts that are kept in the system are dumped into the evaporation ponds. As a result, the system retains 14.4 MT of salts annually (Karki *et al.* 2011). Additionally, to complement the canal water supply, over a million tube wells are pumping water (Kumar *et al.* 2018). Over 70% of tube wells, however, pump sodic water (Qureshi *et al.* 2008). As a result, soils damaged by salt have grown to be a serious threat to irrigation-based agriculture. In Sindh Province, where roughly 54% of the irrigated area is saline due to poor rainfall, high evapotranspiration rates, and shallow saline groundwater, soil salinity problems are particularly severe (Ashraf *et al.* 2012).

4.7. Groundwater depletion

The IBIS was created to provide water to farms on a weekly rotating schedule known as 'warabandi' for a yearly cultivation intensity of 75%. For the time period associated with their lands and cropping pattern, the farmers receive their fair amount of water once each week. The agricultural intensity of farmers who have access to groundwater has grown by more than 150%. The lack of a regulatory framework for groundwater in Pakistan allows anyone to establish any number of tube wells anywhere, at any depth, and to pump any volume of water at any one time (Bhutta & Alam 2006). The groundwater is being drained at an alarming rate as a result of indiscriminate pumping. According to reports, out of 43 canal commands, 26 saw a decrease in water table levels as a result of a sharp rise in groundwater exploitation (Ashraf *et al.* 2007). The situation is considerably worse in Baluchistan, where the water table is dropping by more than 3 m per year in several river basins. The primary causes of this are the province's extremely dry climate and the standard flat electricity rate.

4.8. Neglect of the rain-fed areas

In Pakistan, irrigated agriculture has received the majority of investment during the past 40 years, whereas rain-fed agriculture has mostly been ignored. Of the cultural areas in the nation, the rain-fed areas make up roughly 40%. Major crops in these locations produce yields on average that are well below their potential. The primary causes of this low agricultural productivity are (i) irregular and infrequent rainfall, which stresses plants during critical growth stages; (ii) soil erosion, which causes the loss of water and fertile topsoil; (iii) inefficient use of land and resources as a result of small and fragmented landholdings (Mendes *et al.* 2020); and (iv) low agricultural inputs (Ashraf *et al.* 2007). These areas, however, have a great potential to improve the livelihood and food security of the most vulnerable populations because (i) there is a large gap between the current and potential levels of agricultural productivity (Kummu *et al.* 2016), (ii) they are largely populated by underprivileged communities, and (iii) there is plenty of opportunity to extend the scope of successful interventions. Additionally, extra irrigation, if available, might increase productivity by intensifying and diversifying the crops (Qureshi & Ashraf 2019).

4.9. Indus water treaty

A dispute over water management broke out between India and Pakistan shortly after 1947. The agreement was signed by the World Bank in 1960. This agreement divided the use of canals and rivers between the two nations. Pakistan was given exclusive rights to the three western rivers Indus, Jhelum, and Chenab, while India was allowed to retain its independence over the three eastern rivers Ravi, Beas, and Sutlej. For 10 years, the agreement provided for an undisturbed source of water. During this time, Pakistan built huge dams, which were partly financed by long-term loans from the World Bank and Indian compensation capital (Kummu *et al.* 2016). Three mega dams, Tarbela, Mangla, and Warsak, were built. In addition, the framework for connecting the eight canals was created and the newly built tunnels were renovated. This agreement also included the construction of a sluice culvert and five dams. On the other hand, 29.604 BCM provide a full volume of water sufficient to irrigate around 8 million hectares of land. After the 62-million-pound in land waterway, water became scarcer, which meant a significant loss for the country (Khana *et al.* 2020).

5. WATER LOSSES

Pakistan's total accessible water resources together with its canals, waterways, and land losses, are displayed in Figure 8.

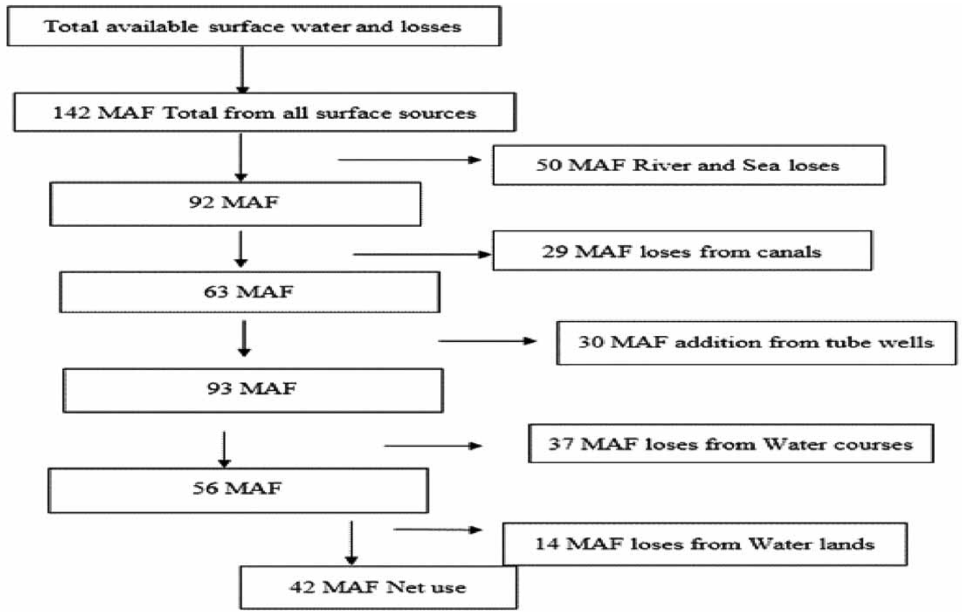

Figure 8 | Total reversibility of water irrigation system in Pakistan (Khoso *et al.* 2015).

6. DISCUSSION

Global ecosystems, economy, and human well-being face serious difficulties as a result of CC. Some of the main effects of CC include rising temperatures, rising sea levels, extreme weather events, and changes in precipitation patterns. Wide-ranging effects of these changes include heightened threats to public health, biodiversity loss, water scarcity, and food security. To reduce greenhouse gas emissions, switch to renewable energy sources, encourage sustainable lifestyles, and prepare for CC, immediate action is required. In order to solve the intricate and interrelated problems brought forth by CC and build a more sustainable and resilient future for future generations, cooperation, innovation, and international cooperation are essential.

7. EFFECTIVE MANAGEMENT STRATEGIES

The current water scarcity in Pakistan makes efficient management of water supply essential. By using certain techniques, it could be feasible to save the 1,603.53 million cubic meters (Frumkin *et al.* 2008) of water that is currently being lost. One of these tactics is to address the significant water losses caused by overflow, seepage, and runoff through clogged canals and waterways (Ayub 2020). Public education and awareness campaigns are essential to educate the public on water conservation techniques and encourage cooperation (Adebayo 2007). Pakistan should introduce water management laws similar to those of western countries. Most of the country's water supply comes from groundwater sources, with over 11.10 BCM available for agricultural use. In other places, however, over-abstraction from tube wells has led to rapid depletion, necessitating government monitoring and replenishment strategies (Table 6).

Important measures include using modern drainage techniques, reusing wastewater for irrigation, and converting the drainage system into a demand-oriented structure. It is necessary to take measures to prevent illegal water extraction and guarantee fair distribution; this may entail involving water users in the nationalization of the drainage distribution network. Furthermore, increasing the cost of water would encourage responsible use and help establish its value (Corcoran 2010). Building, running, and maintaining the drainage system requires cooperation between farmer's institutions, water user associations, and the private sector (Spulber & Sabbaghi 2012). To manage Pakistan's water resources and improve agriculture, effective engineering, scientific understanding, and administrative skills are needed. The nation has succeeded in achieving food self-sufficiency despite population expansion. Pakistan's agriculture sector has flourished since independence, ranking among the top 7 countries in the production of various crops such as chickpea, rice, mango, sugarcane, milk, dates, palm, apricot, wheat, and onion (Khana *et al.* 2020). Despite population growth, the country has achieved food self-sufficiency.

Table 6 | Priority list of WAPDA for major dam building in the future (Khoso *et al.* 2015)

Project (dam)	Rivers	Capacity (MW)	Storage (BCM) gross/live	Estimated cost ($ million)
DiamerBasha	Indus	4,500	9.989/6.4	11,178
Kurram Tangi	Kurran	84	1.480/0.9	700
Golen Gol	Chitral	106	RoR	130
Tarbela 4th Ext.	Indus	1,350	–	826
Munda	Swat	740	1.603/0.7	1,401
Kohala	Jhelum	1,100	RoR	2,400
Bunji	Indus	7,100	RoR	6,838
Dasu	Indus	4,320	1.418/7.9	5,206

RoR, run of river; WAPDA, Pakistan Water and Power development Authority.

8. WATER SECTOR POLICIES AND ADAPTIVE STRATEGIES

The goals of the National Water Policy are to protect and preserve ecosystems that depend on water as well as the environment. Environmental sustainability must be guaranteed, and Environment impact Assessment (EIA) studies must be conducted concurrently with project feasibility studies for water resources, according to related planning concepts. It is also necessary to guarantee consistency with social acceptability, environmental sustainability, and economic viability. Water, energy, and food security, as well as climate-related disasters, should all be taken into consideration while conducting an assessment of CC mitigation and adaptation 'for sustainable water resource development and management'. The 18th constitutional amendment makes agriculture and irrigation, the environment, and water-related subsectors provincial matters even though water is a national duty (Waheed *et al.* 2021). Although Gilgit-Baltistan (GB) adopted the National Water Policy and Khyber Pakhtunkhwa (KP) created a drinking water policy in 2015, both countries have yet to create their own water management policies. In keeping with the provisions of the KP Environmental Act of 2014 and the National Environmental Policy, this pledges to 'take measures [that will be taken to identify, protect, develop, and conserve surface and ground water resources]'. It also emphasizes the importance of conserving water resources. Additionally, it says that 'in planning and development of water supply scheme, due consideration will be given to the adverse impacts of Climate Change, vulnerability and fragility' (Waheed *et al.* 2021). Nevertheless, there is no mention of adaptation or mitigation strategies for the management of water resources. 'Policy measures related to water resources applicable to Punjab (PB) in line with the National Climate Change Policy (NCCP) 2012 should be adopted', according to PB's Water Policy, although it does not specify how they would be delivered. Although adaptability is acknowledged, CC mitigation tactics and initiatives are not highlighted in the policy. It is mentioned that adaptation strategies should be developed to lessen the effects of CC. The environment is acknowledged as a policy objective by the Environmental Protection Agency (EPA), which seeks to 'ensure effective enforcement of regulations for managing the health of acquirers in collaboration with EPA', and environmental concerns are highlighted in PB's Water Policy (2018). There are no specific policies in the water sector that address CC adaptation and mitigation mainstreaming.

8.1. Policy recommendation

Pakistan must find comprehensive approaches to address the complex problems associated with water management. These difficulties include inadequate legislative reforms, poor irrigation practices, problems with infrastructure development, urbanization's burden on water resources, pollution from water sources, and the effects of CC. Large-scale infrastructure development is emphasized in water policy circles as a means of preventing sedimentation and storage loss. Nonetheless, it is critical to understand how Pakistan's food and water security are threatened by CC-related vulnerabilities in agriculture and inadequate water management techniques. The current pandemic has made the shortage of water supplies much worse and raised the occurrence of illnesses that are transmitted through the water. Water-saving measures, better irrigation systems, and efficient water distribution are just a few of the effective water management solutions that must be put into practice to solve these intricate water-related issues. Coherent policy, reliable governance and water treatment infrastructure, and the investigation of alternate water purification technologies are also crucial. Comparative studies of how vulnerable agricultural households are to CC in other nations, like Vietnam, Cambodia, and Myanmar, provide insightful information that is applicable to Pakistan. Pakistan can mitigate the impact of water scarcity on farm households and foster resilience against the effects of CC by implementing suggested policy measures like improving early warning systems, augmenting public funding for infrastructure development, and strengthening adaptive capacity. The study's approach for evaluating livelihood risk is a useful resource for comprehending and resolving the particular issues that Pakistani farm households are facing in light of CC (Minh *et al.* 2023).

8.1.1. Stakeholder engagement and community participation

Policymakers, water managers, and local communities are among the important stakeholders who must actively participate in Pakistani efforts to improve water resource management and development. Involving these parties promotes ownership, cooperation, and the long-term sustainability of projects. In this regard, a 4-year study project in Pakistan aimed to improve groundwater management through the establishment of professional relationships between farming communities, university researchers, and groundwater managers. Improved groundwater monitoring skills and a greater comprehension of the social and economic effects of water use were the results of this cooperative approach. In a similar vein, Pakistan's National Water Policy (NWPP) acknowledges that stakeholder involvement is essential when tackling issues related to water security. The absence of a clear framework and effective procedures for implementation in the policy has led to the involvement of important stakeholders in the NWPP's participatory process. In order to secure local communities' active engagement and the achievement of development goals, the China-Pakistan Economic Corridor (CPEC) project's success also depends on incorporating them in decision-making processes and project implementation. In a distinct setting, corporate governance, waste and effluent disclosure, and firm performance in polluting industry enterprises were examined in an Indonesian study. Waste and effluent disclosure policies were found to be highly influenced by a number of corporate governance criteria, including board gender diversity, board independence, board attention, and audit committee effectiveness. The study could not discover any evidence of a substantial relationship between waste and effluent disclosure and corporate performance as determined by return on assets (ROA). These results advance knowledge of the connection between environmental disclosure and corporate governance in Indonesia's polluting industries. The study emphasizes how crucial it is to implement sound corporate governance procedures in order to encourage accountability and openness in the disclosure of waste and effluent. Furthermore, in concentrating on waste and effluent disclosure in particular industries, it broadens the body of knowledge already available on corporate social responsibility (CSR) and sustainability reporting. Policymakers and stakeholders can improve waste and effluent disclosure practices in polluting businesses by developing policies based on the practical implications of these findings. In summary, this study offers significant understanding of how corporate governance contributes to environmental sustainability and transparency in Indonesia's polluting sectors (Tasya & Kusumaning 2023).

8.1.2. The CPEC and CC

A $62 billion construction project within China's Belt and Road Initiative (BRI), the CPEC was launched in 2017 and is expected to run until 2030 (Kouser *et al.* 2020). It is generally recognized as a major shift in the geopolitical and economic landscape of the area. 70% of the total investment is anticipated to come from foreign direct investment (FDI) in Pakistan (Husain 2018). CPEC's monetary worth surpasses Pakistan's total FDI received since 1970 (Ghani & Sharma 2018; Waheed *et al.* 2021). Infrastructure and energy projects are the main areas of interest for the CPEC investment (Vats 2016; Mehar 2017). By 2030, these projects are expected to boost Pakistan's gross domestic product (GDP) growth to 7.5% annually (Mirza *et al.* 2019). Under the CPEC plan (2017–2030), the main sectors of cooperation are energy, trade, industrial park development, infrastructure development, agriculture, tourism, and financial cooperation. The Chashma Right Bank Canal project in Khyber-Pakhtunkhwa, which seeks to cultivate 300,000 acres of fertile land (Kouser *et al.* 2020), is one of the steps the CPEC has taken to solve irrigation water provision; however, this project is still in the planning stages. Given Pakistan's approaching ecological and water catastrophe, more work is needed to guarantee food and water security. China and Pakistan should jointly develop cooperative research institutions to address water constraint and improve Pakistan's agricultural output. Research and development of crops with reduced water requirements would be the main emphasis of these centers. For example, China has successfully created cutting-edge irrigation techniques like drip irrigation, which have enhanced production by 20% and decreased the water cost of cotton crops by 25% (Yadav *et al.* 2019). Policies should also be put in place to swap out low-value and high-demanding crops like sugarcane with high-value and low-demanding crops like sunflowers. During periods of water scarcity, it is essential to educate farmers through awareness campaigns and demonstrations in order to prevent the continuation of water mismanagement problems. It will be advantageous to promote collaboration between Chinese and Pakistani research and awareness institutes because investment in organizations equipped to handle these responsibilities is required.

8.1.3. Proposed policy framework

Several recommendations are made after conducting a comprehensive analysis of Pakistan's water resources, storage, distribution, governance, management, adoption of laws and regulations, and the gap between future water demand and supply. These recommendations will serve as policy input for Pakistan's relevant ministries and organizations. The main goals of the proposed framework are to establish effective water governance and connect SDGs and MDGs related to water by 2030 for Pakistan's sustainable development. In order to achieve the best results, the effective water governance model proposed in Figure 9 takes into account synergistic coordination with important stakeholders, relevant institutions, a regulatory framework, and strong leadership commitments at all levels. The suggested water governance model's crucial components are political commitment and leadership for developing and putting into effect policies. Building institutional capacity, involving stakeholders, and utilizing technology are key pillars of effective resource management.

8.1.4. Integrated Water Resources Management (IWRM)

Implement an integrated strategy for managing water resources that considers the interconnections between different sectors, such as agriculture, industry, and domestic use. In order to ensure the equal distribution and sustainable use of water resources, this strategy entails integrated planning, allocation, and management of those resources. To handle water issues holistically, the 'whole of government' and 'whole of nation' approaches are advised. The proposed strategy should be capable of addressing both current and emerging issues, including those caused by CC, the utilization of surface and groundwater, urbanization, industry, and pollution that deteriorates water quality.

8.1.5. Storage and efficiency

Farms do not receive more than 50% of the water extracted from the Indus River system. Effective steps must be taken to prevent water loss; for instance, the nation should restore its canal network to reduce leaks and unauthorized breaches. A quick water supply system can reduce leakage by at least one-third even while effective canal systems cannot be implemented right once. Similar to this, efficient management of their abstraction and usage for irrigation can be used to undertake groundwater conservation measures. Maintenance and effectiveness should get special consideration in the realm of water demand

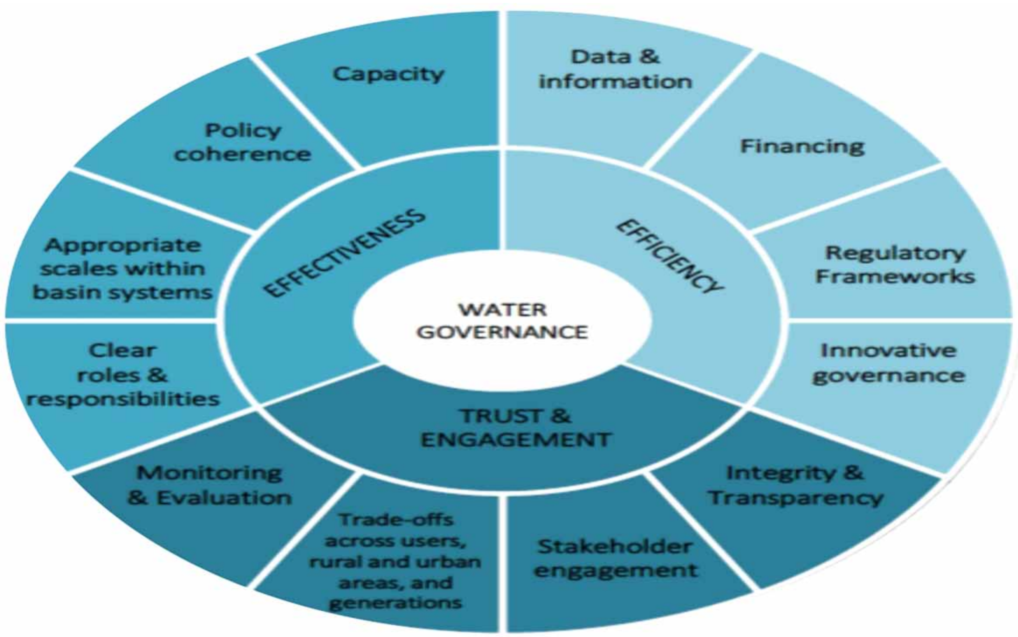

Figure 9 | OECD principles in water governance (Keller & Hartmann, 2020; Kumar *et al.* 2021).

management. Supply is the main focus of the present policy. It is critical to distinguish between efficiency, which involves eliminating waste, and working harder with fewer resources, saving money, and reducing consumption.

8.1.6. Water conservation

Conservation is a crucial step in lessening the impact of CC on water resources. Although relying solely on storage is not a long-term solution, it becomes crucial to store additional water if the rainfall is unreliable, the yearly rainfall is above average, or if the rainfall decreases in the upcoming years. The release, storage, and rehabilitation of water during the dry season should all be considered in a comprehensive national conservation plan and irrigation system. Additionally, there is a significant opportunity for small- and medium-sized dams to extend the lifespan of current storage facilities and enhance their infrastructure. Water availability for irrigation and other uses increases with an increase in the water reservoir. However, there are also potential issues with water conservation, particularly when water is stored in large dams. These problems include destroying habitats, ocean carbon sinks, and disadvantaged communities.

8.1.7. Infrastructure that is climate-resilient

To make water infrastructure systems more resistant to the effects of CC, develop and enhance it. In spite of the fact that the need for more dams has been recognized over the past four decades, they have not been built due to insignificant political grudges that have strained the federating units. Given that Pakistan is currently in a precarious position and is only 3 years away from being designated as a country with a water shortage, it is imperative to utilize all elements of national power (ENP) to achieve consensus, secure funding, and expedite the construction of more dams. While the CPEC is more focused on infrastructure development, a portion of it could be renegotiated for the construction of water reservoirs. The pace of the ongoing Diemer and Bhasha projects should also be accelerated. The Ministry of Planning Commission should also collaborate with all stakeholders to develop a comprehensive roadmap for the sustainable development, conservation, and efficient utilization of water resources over the next 15–20 years. Silting has significantly reduced the capacity of Mangla, Tarbela, and Chashma, which needs to be repaired right away.

8.1.8. Establishment of a groundwater regulatory authority

Implement sustainable groundwater management techniques to prevent excessive use of aquifers and mitigate depletion. This can involve taking measures such as monitoring groundwater levels, regulating pumping rates, promoting artificial recharge techniques, and preventing illegal well drilling. To mitigate and control excessive groundwater extraction, it is necessary to establish a regulatory framework for the installation and operation of tube wells. In particular, subsidies for electricity tariffs of groundwater users should be withdrawn.

8.1.9. Water governance and institutional reforms

In Pakistan, an attempt was made to introduce an environmental law in 1977. The nation created a National Conservation Strategy (NCS) in 1992, and the Pakistan Environment Protection Council approved the National Environmental Action Plan (NEAP) in 2001. NEAP addresses issues with air, water, sanitation, soil, forestry, and CC, which present a number of obstacles. The central government must prioritize the creation of policies to ensure sustainable use of surface and groundwater, industrial use, and wastewater management. Due to the interdependence of food, water, and energy security, a comprehensive management system must address all relevant challenges, including groundwater pollution, wastewater treatment, and emissions.

8.2. CC adaptation strategies

Develop and implement water resource management-specific CC adaptation methods. This may involve determining the most effective adaptation strategies, analyzing the risks of CC, and integrating climate resilience into water-related planning and policy processes.

8.2.1. Rainwater harvesting

One of the most significant problems restricting agricultural development in rain-fed areas is water scarcity. Rainfall in these regions ranges from less than 200 mm to more than 1,000 mm per year, with the majority occurring between July and September. This valuable water is lost as surface runoff due to intense, brief rainfalls, a lack of watershed management practices, and the absence of rainwater harvesting activities. Along with the loss of water, fertile topsoil is also lost as a result of this. The water that is currently being lost must be captured as much as possible, either above ground or below ground. During dry seasons, stored water can be used as supplementary irrigation to prevent crop loss.

8.2.2. Public awareness and education

Raise public awareness about the importance of water conservation, promote environmentally sustainable water management practices, and educate about the impact of CC on water resources. Campaigns for education, community involvement, and knowledge-sharing platforms can all help with this. The majority of issues facing the water sector are a result of low literacy rates, as well as a lack of awareness about water conservation techniques and high-efficiency irrigation methods. It is necessary to launch a broad media campaign for societal awareness as well as a village-to-village extension services effort. To effectively communicate innovative irrigation practices, technology, and processes to farmers, it is essential to establish an efficient extension service framework.

It is vital to raise mass public awareness regarding water management in order to engage the public in government campaigns. The most efficient media are print media, which target the educated sector of society, and television and radio for the general populace, which is generally less educated. The issue can be partially addressed by raising awareness and inspiring action at the national level. However, it is also important to make the public aware of the need for their contribution or payment for the services they use. What we've noticed about the general population is that people become more cautious when they realize that they have to pay for whatever they eat, even if it's just a small amount of money. Pure motivation is ineffective because the value of free services is not well communicated.

8.2.3. Recycling and management of wastewater

In developed nations, the sustainable utilization of recycled wastewater for cleaning, washing, and other activities helps decrease the demand for potable water, and developing nations are also making progress in this area. For the wise use of wastewater, Pakistan lacks public–private partnerships and suitable regulations. Wastewater management issues often arise due to distortions caused by ineffective environmental legislation and a lack of institutional capacity for oversight and administration. The most challenging task facing policymakers is to make the public understand the importance of wastewater recycling and to effectively utilize technology. There are few mechanisms in place at the national and provincial levels to address this critical issue, and the rural population is disconnected from mainstream national policies and international best practices. Therefore, the situation will worsen and become more severe as Pakistan approaches the water scarcity threshold over the next 3 years.

8.2.4. Making a self-sustained water sector

Water is a valuable natural resource, but unfortunately, Pakistan lacks the resources to develop the sector. It is the most vital commodity, according to our examination of its consumption, which refers to the link between supply and demand. We require a 'Water Vision' with resources, also known as a long-term water sector development strategy (WSDS). At all levels of the government apparatus, there is a need to establish a comprehensive water sector that is economically and environmentally sustainable. Constitutional modifications are necessary to achieve this goal. At the federal, provincial, and local government levels, we need a collaborative effort between the public and private sectors to effectively manage water resources.

8.2.5. Inefficient use and unfair distribution

Inefficient water use and unequal distribution are the root causes of socio-political discontent and unacceptable water waste. This is particularly true for irrigation water, as its unfair allocation generates feelings of scarcity and dissatisfaction among certain societal groups, while also contributing to water waste due to inefficient usage. A thorough assessment of the situation is necessary to ensure equitable allocation among all water users. Second, we must train our farmers to effectively use water in the context of modern technology, employing appropriate crop patterns and field water management. The lining of water channels with bricks, which has already begun in Punjab, will also significantly reduce water wastage.

9. CONCLUSION

Pakistan's water security is seriously dangerous by CC, which will exacerbate the country's existing water crisis. CC is accelerating the melting of the Himalayan glaciers, which are a major source of water for Pakistan, one of the most water-scarce countries in the world. As a result, Pakistan is experiencing longer and more severe droughts and more frequent and severe flooding. Unpredictable rainfall patterns make water availability even more challenging, making it difficult for farmers to plant crops and for water managers to allocate resources effectively. These water issues have a profound impact on Pakistan's economy and society, jeopardizing food security, increasing the prevalence of water-borne infections, and leading to displacement. Immediate action is needed to tackle the water problem. This includes investing in water efficiency, water conservation, and the development of alternative water sources. To mitigate the effects of climate change on water resources, a combination of strategies, including water conservation, infrastructure upgrades, alternative supply development, and improved resource management, is essential.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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