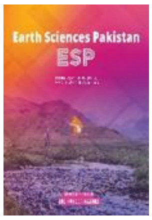
ZIBELINE INTERNATIONAL™ PUBLISHING

Earth Sciences Pakistan (ESP)

DOI: http://doi.org/10.26480/esp.01.2026.47.57

ISSN: 2521-2893 (Print)
ISSN: 2521-2907 (Online)
CODEN: ESPADC



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REVIEW ARTICLE

UNDERSTANDING THE SPATIOTEMPORAL HYDROLOGICAL VARIABILITY AND ANTHROPOGENIC DRIVERS OF CHANGE IN PAKISTAN'S INDUS BASIN

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ARTICLE DETAILS

Article History:

Received 26 April 2026
Revised 20 May 2026
Accepted 25 June 2026
Available online 01 July 2026

ABSTRACT

Pakistan occupies a highly vulnerable position at the intersection of climate-sensitive mountain hydrology and one of the world's most intensive irrigation systems. The country's water sector is under increasing pressure from climate variability, glacier change, groundwater depletion, inefficient irrigation infrastructure, and fragmented governance. This review synthesizes evidence from hydrology, cryosphere science, agriculture, and water governance to provide an integrated assessment of Pakistan's water resources across historical, contemporary, and future dimensions. It traces the evolution of water development from the Indus Valley Civilization through the colonial canal era and the post-Indus Waters Treaty period and then examines the present hydrological regime across surface-water, groundwater, rainfall, and glacier-fed systems. The analysis shows that Pakistan receives substantial renewable water resources, but their availability is highly seasonal, spatially uneven, and increasingly compromised by over-abstraction and system inefficiencies. Groundwater depletion is most severe in Punjab, while Sindh faces salinity, drainage failure, and reduced downstream flows; Khyber Pakhtunkhwa is exposed to flood and cryosphere-related hazards; and Balochistan remains under chronic water scarcity. Climate change is intensifying floods, droughts, and uncertainty about meltwater, further increasing water insecurity. The review concludes that Pakistan's water crisis is not only a problem of scarcity, but also of governance, storage limitations, and low irrigation efficiency. Sustainable water security will require integrated surface-groundwater management, improved monitoring using remote sensing, stronger institutional coordination, and climate-informed water planning.

KEYWORDS

Pakistan, Indus Basin; groundwater depletion; climate change; Integrated Water Resources Management

1. INTRODUCTION

Freshwater scarcity has become one of the major challenges of the twenty-first century. Right now, around 4 billion people face serious water shortages for at least one month each year (Mekonnen and Hoekstra, 2016). Projections indicate that by 2030, demand could exceed renewable water supplies by up to 40% if current trends continue (United Nations, 2023). Among the regions most affected is South Asia, home to nearly two billion people, where water security issues are especially severe. These problems are largely due to the vulnerability of monsoon-dependent and glacier-fed rivers to human-induced climate change. Pakistan faces many challenges, sitting at the crossroads of climate, water, and socioeconomic issues. With over 230 million people, agriculture accounts for about 19% of its economy and uses more than 90% of the country's water (World Bank, 2022).

How well the country develops is closely tied to its water systems. The amount of water available per person has dropped drastically from about 5,200 m^3 per year at independence in 1947 to less than 1,000 m^3 today, placing Pakistan well within the water-scarcity zone as defined by (Falkenmark, 1989). This decline is not just about water; it's a result of rapid population growth, increased farming, insufficient infrastructure, and fragmented institutions.

The Indus Basin, Pakistan's main hydrological area, is known as the world's most irrigation-intensive river basin (Biemans et al., 2019). It receives water from snowmelt and glacial melt from the Karakoram, Hindu Kush, and Himalayan mountain ranges, with additional support from the South Asian Monsoon. This vital system irrigates about 22 million hectares of farmland (FAO AQUASTAT, 2021).

However, beneath this apparent abundance lies significant vulnerabilities: ongoing overuse of groundwater, aging irrigation channels, worsening waterlogging and soil salinity, and heightened risks of floods and droughts as climate warms.

Despite a growing body of sub-sectoral literature, including seminal analyses of Karakoram glaciology, groundwater depletion, and climate-hydrology-land use interactions, a critical analytical gap remains: no comprehensive review has synthesized these domains within a unified historical-contemporary-future framework linked to governance analysis at the sub-national level (Archer and Fowler, 2004; Farinotti et al., 2020; Qureshi et al., 2010; MacDonald et al., 2016; Hannan et al., 2024; Immerzeel et al., 2010, 2013; Hannan et al., 2025). The present review addresses this gap directly.The specific objectives of this paper are to: (i) reconstruct the historical evolution of water resource development in Pakistan from the pre-colonial to the present; (ii) characterize the current

Quick Response Code	Access this article online	
	Website: www.earthsciencespakistan.com	**DOI:** 10.26480/esp.01.2026.47.57

Cite The Article: Muhammad Hannan, Muhammad Waqas, Muzafar Ali, Shahzaib Channa, Muhammad Asim Kandhro, Muhammad Usman Khalid (2026). Understanding The Spatiotemporal Hydrological Variability And Anthropogenic Drivers Of Change In Pakistan's Indus Basin. *Earth Sciences Pakistan, (ESP), 10, (1)*: 47-57

hydrological regime across surface water, groundwater, and cryosphere subsystems; (iii) analyze provincial disparities in water resources and management; (iv) quantify the principal challenges facing Pakistan's water sector; and (v) develop evidence-based pathways toward sustainable water governance under climatic and anthropogenic pressures. Figure 1 illustrates the interplay between climatic drivers (glacier melt, rainfall) and anthropogenic stressors (urban demand, over-extraction) across the surface and subsurface layers. Key features include the Indus River system, irrigation networks, and aquifers, highlighting resulting environmental impacts such as groundwater depletion and coastal salinity intrusion.

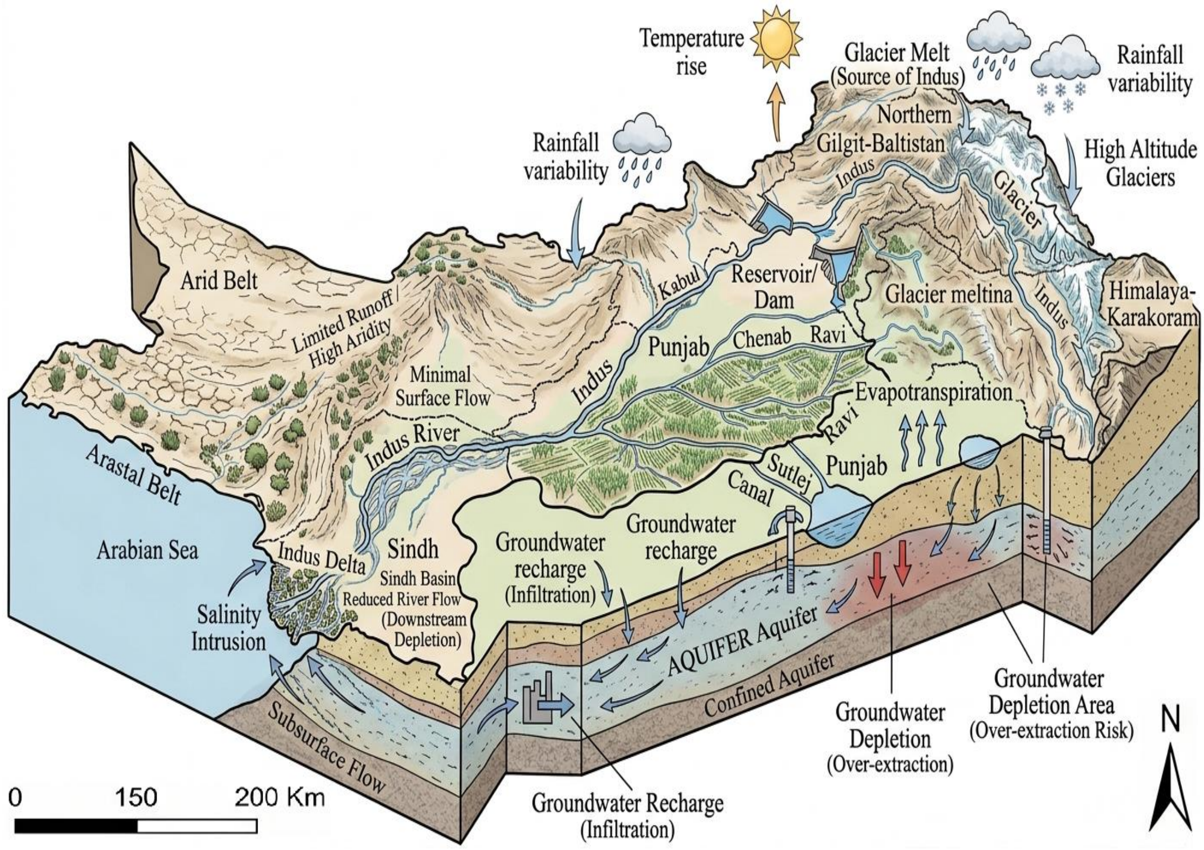

Figure 1: A schematic of Pakistan's Indus Basin hydrological system.

2. Historical Evolution of Water Resources in Pakistan

2.1 Indus Valley Civilization and Pre-Colonial Water Systems

The hydraulic ingenuity of the Indus Valley Civilization (3300-1300 BCE) predates most modern irrigation approaches by thousands of years. Archaeological finds at Mohenjo-daro, Harappa, and Dholavira reveal advanced urban water management systems, including covered drains, stepped wells, and what appear to be early irrigation earthworks aligned with seasonal floodplains (Kenoyer, 1998). While scholars still debate the scale and organization of irrigation agriculture during this era, the placement of Indus settlements along the Indus, Ravi, and Ghaggar-Hakra rivers strongly suggests reliance on alluvial water and seasonal flooding cycles (Wright, 2010). In the period before and during the Mughal era (1526-1857), irrigation development in Punjab and Sindh involved both government-led canal projects and community-managed karez (underground aqueduct) systems, especially common in modern Balochistan and the tribal areas of Khyber Pakhtunkhwa (KP). The karez, a type of Persian qanat, is a gravity-based groundwater extraction method with a remarkable history and can transport water over tens of kilometers without mechanical assistance (Lightfoot, 1996). It's estimated that thousands of karez systems operated in Balochistan around the time of British annexation, highlighting a long-standing hydraulic expertise often overlooked in mainstream histories.

2.2 Colonial Irrigation Development and Canal Colonization

The British colonial period (1849-1947) marked one of the most exciting chapters in the history of hydraulic engineering in the subcontinent. Recognizing the promise of irrigated agriculture in Punjab, the colonial authorities launched large-scale canal projects, beginning with the Upper Bari Doab Canal in 1859. This was followed by an ambitious plan to create 'canal colonies in the late nineteenth and early twentieth centuries. By 1947, Pakistan had inherited about 14 million hectares of irrigated land, supported by a vast system comprising 3 major reservoirs, 43 diversion weirs, 12 inter-river link canals, and roughly 60,000 km of channels. The World Bank later called this system 'the largest contiguous irrigation network in the world' (Briscoe & Qamar, 2006). The engineering approach was primarily hydraulic-gravitational: water was diverted from high-gradient rivers at barrages and channeled through a hierarchy of canals, distributaries, and watercourses, all designed to flow continuously without pressure. While this system worked well, it overlooked the importance of drainage infrastructure, leading to waterlogging and salinity problems that became prominent after independence (Hussain et al., 2017). Additionally, the colonial management style was highly top-down and supply-focused, making it difficult to implement reforms later.

2.3 The Indus Waters Treaty and Post-Partition Transformation

The 1947 partition split the Indus irrigation system, cutting off the crucial headworks of canals allocated to India, leaving Pakistan heavily reliant on water from Indian-controlled territories. To ease water disputes, the Indus Waters Treaty (IWT) was proposed in 1960, with the World Bank facilitating negotiations between India and Pakistan. Under the treaty, the three western rivers (Indus, Jhelum, Chenab) were assigned to Pakistan, while India received the three eastern rivers (Ravi, Beas, Sutlej).

The treaty also included compensation measures and a 10-year transition plan (Salman and Uprety, 2002). This agreement spurred a large-scale effort to improve water infrastructure in Pakistan, partly funded by loans from the World Bank and other donors. Between 1960 and 1976, the Indus Basin Works program built major projects such as the Tarbela Dam (completed in 1976 with a capacity of 13.7 BCM), the Mangla Dam (completed in 1967, initially 7.25 BCM but later increased to 9.12 BCM), and a complex system of link canals designed to transfer water from the western rivers to compensate for the lost eastern supplies.

Overall, this infrastructure significantly increased Pakistan's water storage capacity, but it also centralized control within federal institutions, which later posed governance challenges.

2.4 Expansion of Canal Irrigation and Groundwater Development

The post-IWT era, spanning the 1970s and 1980s, saw a remarkable surge in canal irrigation and groundwater use. The rollout of Green Revolution technology, featuring high-yielding seed varieties, synthetic fertilizers, and mechanized tube wells, spurred rapid growth in groundwater extraction, especially in Punjab. The number of registered tube wells rose from about 11,000 in 1960 to over 400,000 by 1990 and surpassed 1.2

million by 2015 (PCRWR, 2019). While this expansion greatly boosted agricultural productivity, it also raised concerns about the unsustainable depletion of aquifers and, in saline-water zones, the upward movement of brackish groundwater into the root zone. All these evaluations are well explained in Figure 2, highlighting key infrastructural developments, groundwater expansion, and institutional transformations.

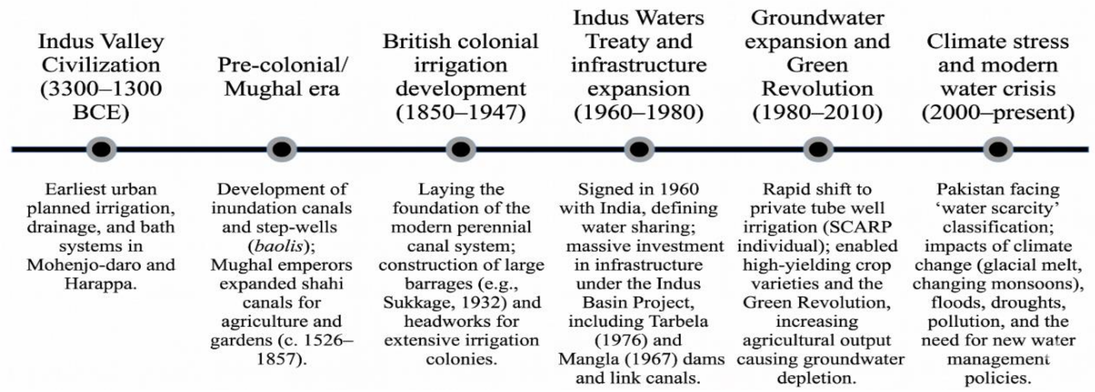

Figure 2: Historical evolution of water resource development in Pakistan. Timeline showing major phases from the Indus Valley Civilization to the modern climate stress era.

3. Hydrological Framework of Pakistan

3.1 Surface Water System

3.1.1 The Indus River System

The Indus River begins at Lake Mansarovar on the Tibetan Plateau, at an elevation of about 5,182 meters above sea level and drains a vast basin of 1.12 million square kilometers, with about 52% of it lying within Pakistan (Figure 3). This river forms the heart of the country's water system. The main tributaries (Kabul, Swat, Jhelum, Chenab, Ravi, Beas, and Sutlej) combine to create the upper Indus Basin (UIB), known for its complex glacial and hydrological features, making it one of the most intricate river systems on Earth (Immerzeel et al., 2010).

At the Attock gauge, where the Indus and Kabul rivers meet, the average yearly water flow is about 2,800 cubic meters per second. However, this number can vary greatly from year to year, with variations exceeding 0.35 due to factors such as glacial melt cycles, changes in snowpack, and monsoon weather patterns (Archer, 2003).

Across Pakistan, the total annual flow of the Indus is usually estimated to be between 180 and 200 billion cubic meters, though this can fluctuate over decades because of large-scale climate patterns such as El Niño-Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO). Studies show that drier years in the Indus are often linked to positive phases of ENSO, suggesting that, as climate change may intensify ENSO variability, it could directly affect Pakistan's water availability (Archer and Fowler, 2004). The UIB stands out for its unique dual-driver hydrology. River flows in the northern sub-catchments, such as Chitral, Hunza, and Gilgit, are primarily fed by snowmelt and glaciers, peaking from June to August. By contrast, flows in the southern and eastern parts, including the Jhelum, Chenab, and Ravi, are driven mainly by the monsoon and peak between July and September. This overlap of melt and monsoon peaks can create combined flood risks, but it also provides a reliable period of high flows essential for canal diversions. Notably, the Karakoram Range, which accounts for about 35-40% of the Indus River flow despite covering just 15% of the UIB area, has a significant hydrological impact thanks to its high-altitude glaciers, which serve as a vital reservoir (Immerzeel et al., 2010).

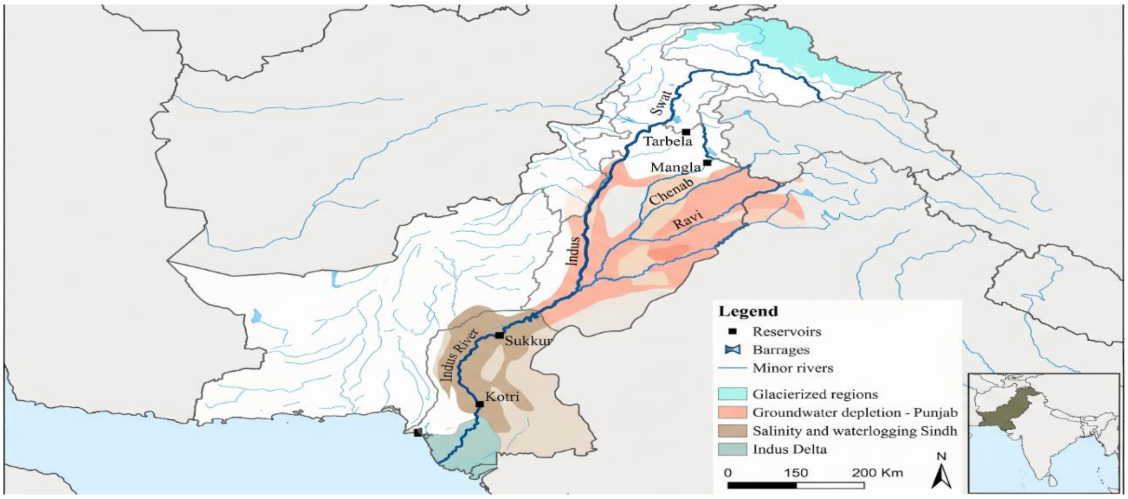

Figure 3: Map of Pakistan showing hydrological features including the Indus River, major tributaries (Jhelum, Chenab, Ravi, Kabul, Swat), groundwater depletion zones in Punjab and salinity/waterlogging zones in Sindh.

Table 1 shows the renewable surface water resources by hydrological zone. Pakistan's surface water mainly comes from the Indus River and its five major tributaries, which together provide about 228.8 BCM of renewable water resources each year. The flow varies greatly with the seasons, as 70-80% of the annual river flow occurs during the monsoon months of July to September.

Table 1: Renewable Surface Water Resources by Hydrological Zone.

Hydrological Zone	External Sources (BCM)	Internal Surface Runoff (BCM)	Groundwater/Rain Recharge (BCM)	Total Renewable (BCM)
Indus Basin Zone	170.5 (Indus, Jhelum, Chenab)	32.6	12.7	219.1
Kharan Desert Zone	0.0	5.5	0.7	6.2
Makran Coastal Zone	0.0	2.9	0.6	3.5
Total	**170.5**	**41.0**	**14.0**	**228.8**

3.2 Groundwater System

3.2.1 Aquifer Characteristics

The Indus Basin aquifer system, which includes the Punjab alluvial plains, the Sindh lower Indus plain, and, to a lesser extent, the piedmont aquifers of KP and Balochistan, is one of the largest and most heavily used groundwater resources in Asia. The unconfined alluvial aquifer in Punjab reaches depths of 150-300 meters, with transmissivity typically ranging from 500 to 5,000 m^2 per day and specific yields of 0.1-0.25 (WAPDA Groundwater Surveys, cited in Qureshi et al., 2010). Groundwater quality varies across space and time: in the upper Rechna, Bari, and Chaj doabs (inter-fluvial zones), water tables are typically shallow (less than 5 meters), and salinity can become quite high due to waterlogging and capillary rise. Meanwhile, in the lower Bari Doab and the central Punjab highlands, water tables are deeper, and water quality is generally suitable for irrigation.

3.2.2 Abstraction Trends and Depletion

Groundwater use in Pakistan has been steadily rising since the 1960s, reaching an estimated 60-70 BCM per year by the early 2000s (FAO AQUASTAT, 2021). This amount far exceeds the natural recharge rate, which was about 40-50 BCM per year before intensive use began, indicating ongoing overuse of the aquifers. GRACE satellite data provide the clearest regional evidence of this depletion. For example, a group researcher found a loss of groundwater storage in the Indus alluvial region of about $-11.4 \pm 2.4\ km^3$ per year from 2002 to 2015, with the most significant reductions occurring in irrigated Punjab (MacDonald et al., 2016). This aligns with direct observations of water table declines of 0.3-1.0 meters annually in parts of central Punjab (Ahmad et al., 2014).

3.2.3 Role of Tube Wells and Agricultural Dependency

The tube well has become the primary method for groundwater extraction in Pakistan's irrigated areas, with over 1.2 million in use across Punjab and Sindh as of 2019 (PCRWR, 2019). Most of these wells are privately owned and operated by individuals, with little regulatory oversight. This situation, in which extraction is driven primarily by energy costs and farming needs rather than aquifer management, reflects a common 'tragedy of the commons' scenario (Ostrom, 1990). Although energy subsidies for agricultural tube wells in Pakistan are strongly politically supported, they have made it easier for farmers to extract groundwater without considering its true scarcity, thereby accelerating the depletion of this vital resource, which might otherwise have slowed as pumping costs increased.

3.3 Cryosphere Contribution

3.3.1 Glacial Extent and Hydrology

Pakistan is home to about 7,253 km^2 of glaciers spread across the Karakoram, Hindu Kush, and western Himalayan ranges (Mustafa et al., 2021; Waqas et al., 2025). This makes it one of the most glacier-rich countries outside the polar regions. The Karakoram Range alone boasts more than 7,000 glaciers, including some of the largest temperate glaciers in the world, such as Siachen, which stretches about 76 km, as well as Biafo and Baltoro.

Meltwater from these glaciers provides an estimated 40-50% of the Indus River's total flow during the vital June to August months, acting as a natural buffer that helps regulate annual variations and keeps water flowing during droughts (Immerzeel et al., 2010; Lutz et al., 2014).

3.3.2 The Karakoram Anomaly and Divergent Mass Balance Signals

A fascinating aspect of Pakistan's cryosphere is the Karakoram Anomaly, in which many glaciers in the Karakoram range appear to hold steady or even grow slightly, unlike their neighbours in the Hindu Kush and Himalaya, which are melting more quickly (Hewitt, 2005; Farinotti et al., 2020). A study noted that this anomaly might be linked to increased winter snowfall in the upper Karakoram, while in some study suggested it could be due to changes in weather patterns caused by a weakening jet stream (Archer and Fowler, 2004; Forsythe et al., 2017). Even when glaciers in this region remain balanced overall, substantial meltwater continues to flow due to high rates of melting in a warming climate, so changes in surface area alone don't tell the full story of water runoff. Looking ahead, the picture is not very certain. Projections from the IPCC show that even with moderate warming, glaciers in the Hindu Kush-Himalayas could lose about 36±7% of their current mass by 2100, and under more extreme scenarios, the loss could reach around 65±6% (IPCC, 2021). Researchers like a group researcher have modeled a 'peak water' situation for the upper Indus Basin, where initial melting increases water flow but then declines as glaciers shrink (Lutz et al., 2022). The exact timing of this peak remains uncertain, but it could occur between 2040 and 2070, depending on emissions and specific glacier factors.

3.4 Rainfall and Climate Variability

Pakistan experiences highly diverse rainfall patterns across the country. While some areas, such as the hyper-arid Balochistan plateau and lower Sindh, receive less than 1,500 mm of rain annually, others, such as the Murree Hills and Azad Kashmir, receive over 1,500 mm. Most gauging stations report annual rainfall variability of 30-40%, highlighting significant year-to-year fluctuations. This variability is shaped by the South Asian Monsoon (SAM) and western disturbances (WDs), which together influence Pakistan's seasonal water cycle. The SAM accounts for about 60-70% of the country's total rainfall, mainly from July to September, and most strongly affects the eastern and northern regions. Meanwhile, western disturbances, active from December to March, provide vital winter snowfall to the UIB, supporting water flows through spring and early summer. Recent studies using detailed climate datasets such as CHIRPS and APHRODITE reveal a concerning trend: more intense storms and longer dry periods, aligning with the wet gets wetter, dry gets drier pattern forecast by global climate models as greenhouse gases increase (Hussain et al., 2005; Rasul, 2012).

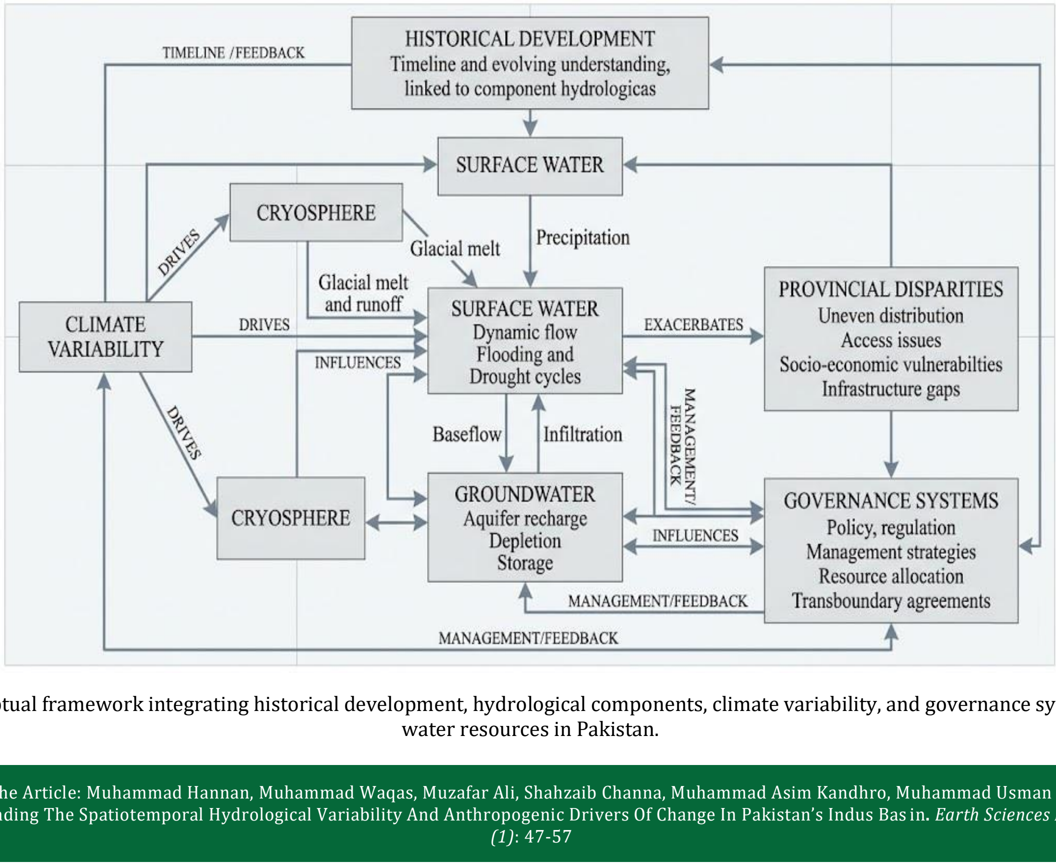

Figure 4: Conceptual framework integrating historical development, hydrological components, climate variability, and governance systems influencing water resources in Pakistan.

4. Provincial Distribution of Water Resources

Water resource availability and management in Pakistan are strongly shaped by the unique geography, climate, and institutional structures of its provinces. A comparison of the four main provinces (Punjab, Sindh, Khyber Pakhtunkhwa (KP), and Balochistan) reveals clear differences in their water systems, infrastructure, and risk levels. Table 2 provides a helpful overview of these differences. Water sharing among provinces is governed by the 1991 Water Apportionment Accord, which allocates water based on an average expected flow of 114.35 MAF (Table 3).

Table 2: Comparative Provincial Water Resources Profile - Pakistan

Parameter	Punjab	Sindh	Khyber Pakhtunkhwa	Balochistan
Area (km^2)	205,344	140,914	74,521	347,190
Primary water source	Canal + groundwater (Indus tributaries)	Indus mainstem (Kotri barrage system)	Glacial & rainfall-fed rivers (Indus headwaters)	Karez (qanat), seasonal streams, limited groundwater
Annual surface water (BCM approx.)	~80-90 BCM allocated via canal	~55-65 BCM (post-Kotri)	~25-30 BCM (mountain rivers)	~5-8 BCM (highly variable)
Irrigation coverage	~75% of cultivated area	~60-65%	~30-40% (terrace/lift)	~15-20% (flood/spate)
Dominant crop system	Wheat-rice, wheat-cotton	Rice-wheat, sugarcane	Maize-wheat, orchard crops	Wheat, fruits (apple, grapes)
Groundwater dependency	Very high; ~0.8-1.0 m/yr decline central Punjab	Moderate; shallow saline aquifers in lower Sindh	Low-moderate; springs and karez predominant	High in certain basins; over-abstraction reported
Key challenges	Waterlogging, salinity, over-extraction, Punjab's flat terrain constrains drainage	Seawater intrusion (Indus delta), sedimentation, drainage failures	Flash flooding, landslides, high inter-annual variability, glacial lake outburst floods (GLOFs)	Severe aridity, karez deterioration, limited recharge, locust and drought cycles
Climate vulnerability	Moderate-High: heat stress, erratic monsoon	High: delta salinization, upstream allocation conflicts	Very High: GLOF risk, accelerated deglaciation	Extreme: persistent drought, limited adaptive capacity
Major infrastructure	Head Islam, Trimmu, Islam Barrages; LBOD	Kotri, Sukkur, Guddu Barrages; Right Bank Canal	Tarbela Dam, Warsak Dam, Chashma Barrage	Pat Feeder Canal, Hub Dam, Rod Kohi systems
Governance body	Punjab Irrigation Dept. (PID)	Sindh Irrigation Dept. (SID)	KP Irrigation Dept.	WAPDA / Balochistan ID

Table 3: Provincial Water Apportionment and Challenges.

Province	Entitlement (MAF)	Share of Balance Supplies	Primary Management Challenges
Punjab	55.94	37%	Aquifer depletion; groundwater mining
Sindh	48.76	37%	Seawater intrusion; 57% waterlogging
KPK	5.78 (+3.0)	14%	Topographical constraints; royalty disputes
Balochistan	3.87	12%	Chronic scarcity; Quetta groundwater collapse

4.1 Punjab

Punjab, Pakistan's most populous province with around 120 million residents and a vital agricultural region, uses about 57% of the country's canal water under the 1991 Water Apportionment Accord. It lies above the deepest and most productive part of the Indus alluvial aquifer, making it a key area for groundwater use. Over the years, heavy groundwater extraction has created a mixed hydrogeological landscape: in central and northern Punjab, water tables have dropped by 0.3-1.0 meters per year, while in southern Punjab and parts of Sindh, waterlogging and increasing salinity have taken hold (Ahmad et al., 2014).

GRACE data highlight Punjab as the main area of groundwater depletion in the Indus Basin (MacDonald et al., 2016; Hannan et al., 2024). The main water challenges in Punjab include: (i) rapid groundwater depletion fueled by the widespread use of private tube wells without adequate regulation; (ii) waterlogging covering around 1.5 million hectares in southern districts; (iii) secondary salinization affecting about 4.2 million hectares of farmland; and (iv) conveyance losses in the canal system, estimated at 25-30%, with additional losses on farms reducing overall irrigation efficiency to about 35-45% (Briscoe and Qamar, 2009).

4.2 Sindh

Sindh receives the remaining flow of the Indus River below the Kotri Barrage, but this share has declined sharply due to upstream water use and reservoir management. The Indus Delta, which once covered about 600,000 hectares, has shrunk considerably. Today, it receives only seasonal and flood-dependent flows, with less than 35 BCM reaching below Kotri in most years, well below the ecological minimum of 35-50 BCM annually needed for delta health (Kalair et al., 2021). Additionally, seawater has intruded more than 100 km inland from the Arabian Sea in parts of the delta, rendering large areas that were once fertile farmland unsuitable for agriculture. The lower Indus plain sits atop a vast but mostly saline aquifer system; most shallow groundwater in lower Sindh has high electrical conductivity, exceeding 3 dS m^{-1}, making it less suitable for irrigation. Unfortunately, the drainage infrastructure here faces significant challenges: the Left Bank Outfall Drain (LBOD), built to drain waterlogged, saline land, has structural problems and insufficient capacity. As a result, the area is prone to severe flooding, especially during the monsoon season, with notable floods in 2010 and 2022 when the drainage system was overwhelmed (Ali et al., 2025; Hannan et al., 2026).

4.3 Khyber Pakhtunkhwa

Khyber Pakhtunkhwa lies within the upper Indus headwater region and is hydrologically sustained by glacier- and snow-fed rivers such as the Swat, Kabul, and Chitral, as well as key tributaries of the upper Indus. It is home to Tarbela Dam (the world's largest earth-filled dam), which serves as Pakistan's crucial storage hub. It originally held 11.1 BCM of water, but this has decreased to about 6.8 BCM due to sediment buildup (WAPDA, 2019). The rivers of KP carry a heavy sediment load, partly due to active tectonic uplift and steep catchment slopes, posing significant long-term infrastructure challenges and gradually reducing the lifespan of existing reservoirs. The water risk profile in KP is quite different from that of the plains provinces. Notably, glacial lake outburst floods (GLOFs) present serious threats; more than 3,044 glacial lakes have been identified in Pakistan's icy mountains, with 33 considered potentially dangerous (Ashraf et al., 2012). The 2022 GLOF events, which contributed to devastating summer floods in northern KP and Gilgit-Baltistan, highlight the compounded risks of climate-driven ice melt and heavy monsoon rains. On the other hand, during unusually warm, low-snow winters, low-flow droughts are becoming an increasing concern, especially for winter wheat cultivation in rain-fed (barani) areas of KP.

4.4 Balochistan

Balochistan covers 44% of Pakistan's land area but is home to only about 6% of the population, making it the most water-stressed province by almost any measure. Most provinces receive less than 200 mm of rain each year. Its agriculture mainly relies on rain or surface irrigation. The traditional karez system, once vital for rural water supply, has been gradually abandoned or degraded due to lack of maintenance, deepening water tables, and migration from rural areas (Lightfoot, 1996; UNDP, 2013). The Quetta Valley aquifer, which supplies Balochistan's largest city, has seen groundwater levels decline by more than 1.5 meters per year since the early 1990s, largely due to population growth, urban expansion, and the rise of illegal tube wells (PCRWR, 2019). With no surface storage options and annual rainfall far below what is needed to recharge the water sources, Balochistan faces what many analysts call an imminent water bankruptcy, a situation in which water use exceeds recharge over the long term. Climate models predict that Balochistan will continue to warm, experience more severe droughts, and see less reliable rainfall under all RCP scenarios (Ashraf et al., 2021).

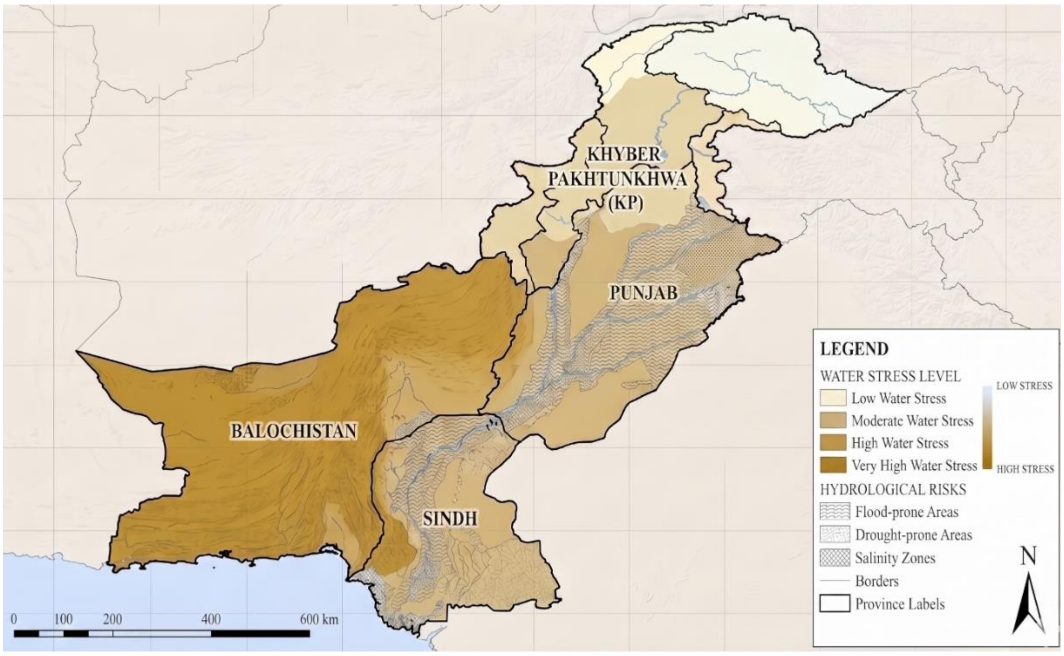

Figure 5: Spatial distribution of provincial-scale distribution of water stress, highlighting regional disparities in water availability and vulnerability.

5. Water Balance and Resource Efficiency

A thorough water balance assessment is essential to understand the ongoing gap between water supply and demand in Pakistan. The country's total renewable freshwater, comprising surface runoff and net groundwater recharge, is estimated at 235-260 BCM annually. Of this, surface water accounts for about 175-185 BCM, while natural groundwater recharge accounts for roughly 50-65 BCM (FAO AQUASTAT, 2021). Total water withdrawals are estimated at about 183 BCM per year, making Pakistan one of the countries with the highest water use relative to its GDP (World Bank, 2022). The country faces a significant structural water deficit, with demand expected to reach 338 km^3 by 2025, compared with a supply of 240-258 km^3. The irrigation system also suffers from high losses: of the 104 MAF withdrawn, 46 MAF are lost in canals and distributaries.

Agricultural water use accounts for about 93% of total withdrawals (~170 BCM), with the remaining 7% used for municipal and industrial purposes. However, much of the surface water that is technically available is not accessible because peak flows occur from June to September, while the highest irrigation demand occurs from October to April for rabi crops and from March to September for kharif crops. This mismatch is compounded by limited active storage capacity. Pakistan's total live storage capacity, roughly 20 BCM across all reservoirs, supports only about 30-40 days of average river flow, far less than in water-stressed countries like Australia or Spain, which have storage for 500-900 days (Abd et al., 2025). This storage gap is one of the biggest structural hurdles to water security in Pakistan. The efficiency of irrigation, which is estimated at 35-45% system-wide, determines how much of the diverted water benefits crops (Briscoe and Qamar, 2009; Qureshi and Perry, 2021).

That means 55-65% of the diverted water is lost to seepage, evaporation, or runoff. Conveyance losses in earthen canals alone account for about 25-30% of the water diverted, while inefficient surface flood irrigation accounts for around 20-30% of losses, especially since 95% of irrigated farmland relies on this method. In contrast, irrigated areas in similar climate zones in the Middle East often achieve application efficiencies of 60-80% thanks to pressurized drip and sprinkler systems. This shows there's significant potential to save water in Pakistan's agriculture without reducing crop yields, simply by adopting more efficient water management practices. Groundwater plays a vital role in the water balance, and Pakistan faces a significant challenge. Currently, groundwater extraction exceeds natural recharge by about 15-25 BCM per year, especially in Punjab. This means much of the country's agricultural water depends on non-renewable groundwater, effectively draining the aquifer of its stored resources. If this situation is not addressed, it could lead to higher pumping costs, increased salinization from deeper, saltier layers, and, eventually, wells drying up in the most heavily used areas.

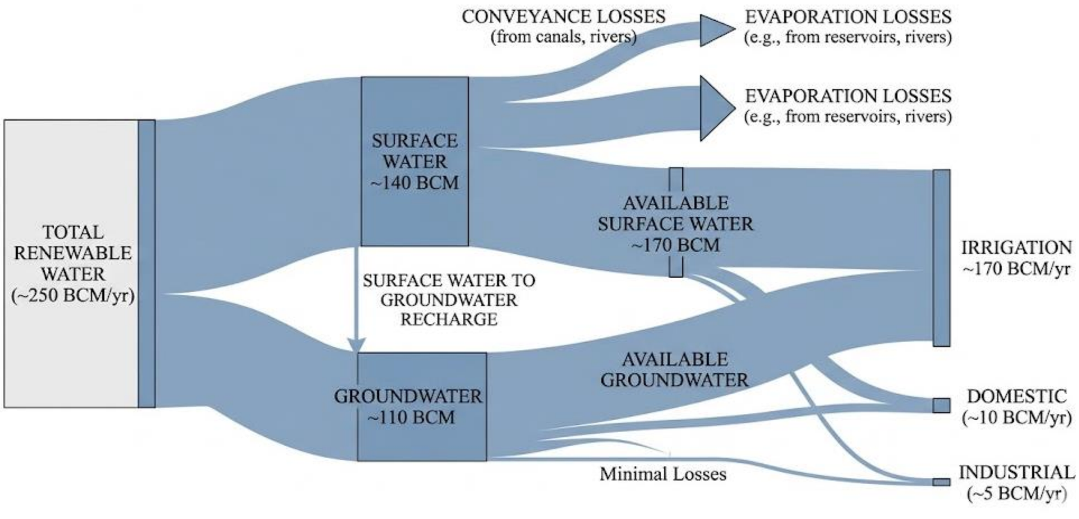

Figure 6: National water balance illustrating renewable supply, sectoral withdrawals, and system losses.

6. Major Challenges

6.1 Groundwater Depletion

Overuse of the Indus Basin aquifer is likely the biggest medium-term risk to Pakistan's water and food security. The GRACE satellite mission, which operated from 2002 to 2017 and has been continued by GRACE-FO since 2018, provided satellite-based measurements of water storage changes at the basin level. A group researcher used this data to pinpoint groundwater depletion in the Indus Basin, finding an average loss of −11.4 ± 2.4 km^3 per year, mainly in the irrigated Punjab plains (MacDonald et al., 2016).

Later studies using GRACE-FO data show that this depletion has continued since 2016, aligning with the ongoing growth of tube-well irrigation (Rodell et al., 2018). The impacts of groundwater loss are not just environmental but also social: large landowners and commercial farms with the resources to drill deeper wells and use diesel pumps can continue extracting water even as shallow water tables drop. Meanwhile, small farmers relying on shallow dug wells face rising costs and increasing well failures, worsening agricultural inequality and rural displacement. This situation creates both a social and a water-related crisis.

6.2 Waterlogging and Soil Salinity

Waterlogging and soil salinization in Pakistan's irrigated plains are serious challenges that damage the land economically. About 6.3 million of the 22 million hectares are affected by salinity, while around 2.3 million are waterlogged, threatening crop roots (PCRWR, 2017; WAPDA, 2018). The SCARP (Salinity Control and Reclamation Project), which began in the 1960s with support from the World Bank and involved over 13,000 public tube wells, has not achieved lasting success due to poor maintenance, high energy costs, and a failure to address the core issue: excessive irrigation water use.

Studies in Punjab and Sindh show that much of this salinization occurs naturally through evaporation from excess irrigation water, largely because Pakistan's canal system has historically provided abundant, subsidized water (Smets et al., 1997; Qureshi et al., 2008). Introducing water-saving irrigation methods and charging for water based on usage could help reduce both waterlogging and salinity, but political and institutional resistance to these reforms remains a significant hurdle.

6.3 Water Quality Degradation

Water quality issues in both surface and groundwater sources pose a serious public health concern. The Pakistan Council of Research in Water Resources (PCRWR) found that about 70% of sampled water sources, whether surface or groundwater, failed to meet WHO standards for at least one parameter, such as physical, chemical, or bacteriological factors (PCRWR, 2017). Sadly, pathogen contamination, especially fecal coliforms, is widespread in urban and peri-urban surface water sources, highlighting the lack of adequate wastewater treatment infrastructure in most cities. Additionally, arsenic contamination in groundwater that exceeds WHO guidelines (10 $\mu g\ L^{-1}$) has been found in several districts of Punjab and KP, posing long-term health risks to communities relying on shallow tube wells for drinking water (Abd et al., 2025). Concerns about fluoride and nitrate levels also persist in certain areas due to local geological conditions. Furthermore, the discharge of industrial waste into the Ravi, Chenab, and lower Indus rivers, mostly untreated due to weak enforcement of regulations, has significantly degraded water quality and harmed aquatic life (Naseer, 2003; Ilyas et al., 2019).

6.4 Infrastructure Inefficiency and Institutional Fragmentation

Pakistan's irrigation system is extensive but faces significant challenges. Over the years, aging infrastructure, sediment buildup, and operational issues have taken a toll. For example, Tarbela Reservoir, the largest storage facility, has lost about 38% of its capacity to sediment since it was built in 1976 (WAPDA, 2019). Similarly, Mangla Reservoir, even after a recent height increase that added around 2.9 BCM of storage, continues to suffer from sedimentation. Notably, there has been no new major storage project since Tarbela, despite several proposals for dams such as Diamer-Bhasha, Dasu, and Mohmand. This is mainly due to budget constraints, disputes over water rights between provinces, and complex geopolitical issues. Moreover, fragmented governance between federal agencies like IRSA and WAPDA and provincial departments, along with the lack of a strong national water law, leads to coordination problems. These issues affect everything from water allocation under the 1991 Accord to licensing tube wells. The 18th Constitutional Amendment in 2010, which transferred many water management responsibilities to provinces without providing enough funding or strengthening institutional capacity, has made coordination even more challenging (Saddiqa et al., 2022).

7. Climate Change Impacts on Pakistan's Water Resources

7.1 Observed Temperature and Precipitation Trends

Analysis of long-term climate data shows a clear warming trend across Pakistan. A group researcher, examining data from 51 gauging stations from 1960 to 2010, found an average warming rate of 0.6-0.9°C per decade in the upper Indus catchments (Hussain et al., 2017). Warming occurs more rapidly above 3,500 meters due to elevation-dependent warming (EDW), which affects snow and ice melt, especially in the Karakoram and Hindu Kush. These patterns align with global findings from the Mountain Research Initiative (MRI, 2015). Precipitation patterns are more varied and less certain. While total annual rainfall does not show a consistent long-term trend across Pakistan, there's a noticeable increase in the frequency and intensity of extreme rainfall events, especially in the upper Indus and northeastern Punjab.

Conversely, Sindh and Balochistan are experiencing prolonged dry periods (Ahmed et al., 2016; Hannan et al., 2026). This shift toward fewer but more intense rainfall episodes reduces groundwater recharge and increases surface runoff, leading to more frequent floods and worsening water scarcity, creating significant challenges for the region.

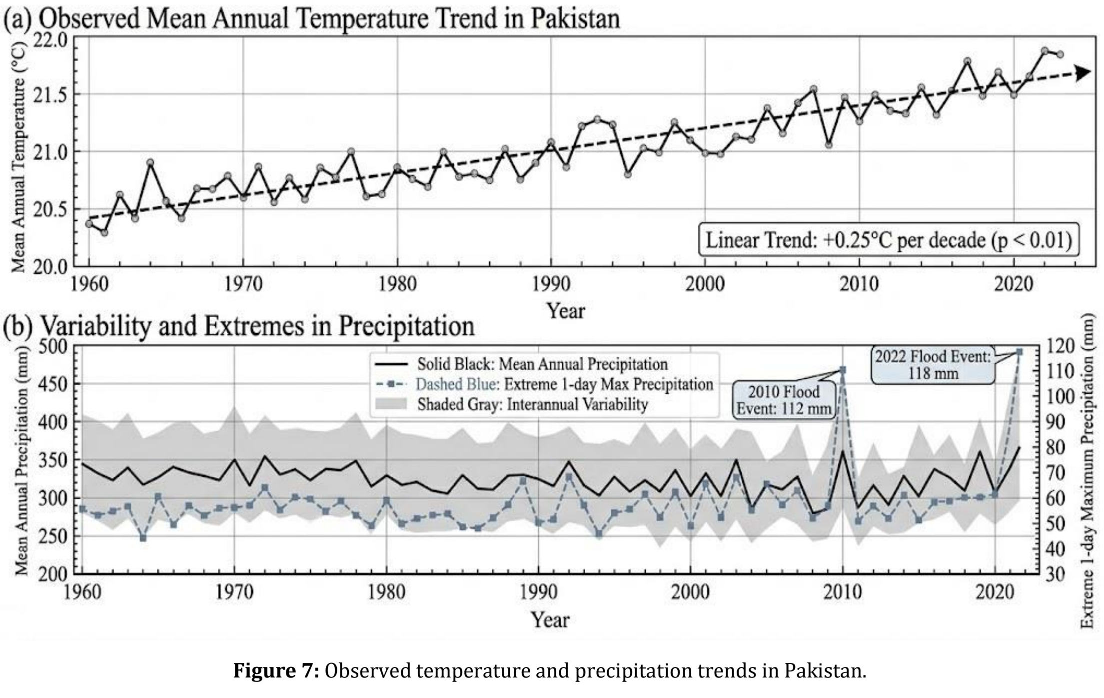

Figure 7: Observed temperature and precipitation trends in Pakistan.

7.2 Glacier Retreat and Meltwater Dynamics

Studies using Landsat, ASTER, and Sentinel-2 imagery reveal a complex pattern of glacier change across Pakistan's mountain ranges. In the Hindu Kush and western Himalayas, scientists have observed area reductions of 0.3-0.8% per year from 1990 to 2020, with signs of acceleration in the past decade (Jha et al., 2025; Kharya et al., 2025).

The central Karakoram presents a more complex picture: while some glaciers exhibit surging and advancing behaviors linked to the Karakoram Anomaly, overall mass balance estimates from geodetic methods suggest near-neutral or slightly negative balances since 2000 (Hewitt, 2005; Farinotti et al., 2020). The impacts of ongoing glacial changes on water resources are significant and differ in the short and long term. In the near future (2020-2050), increased melting of thicker ice due to rising temperatures is expected to boost summer meltwater, possibly increasing the Indus River flow by 10-15% compared to the 1981-2010 baseline (Lutz et al., 2022). However, this boost is temporary. Once glaciers shrink past the 'peak water' point, flows will gradually decrease, reducing the current buffer that supports irrigation during drought years when monsoon rains are weak.

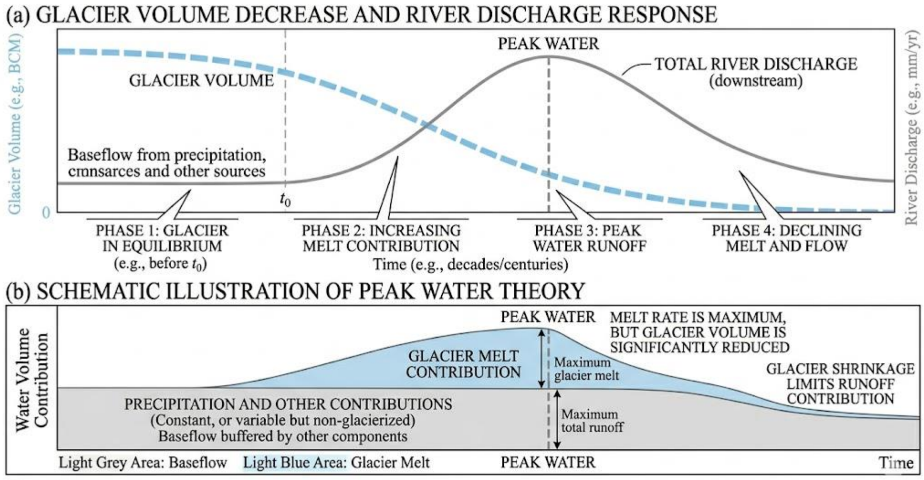

Figure 8: Conceptual representation of glacier melt contribution and peak water dynamics.

7.3 Flood and Drought Frequency

Pakistan has faced increasingly severe climate-related disasters in recent years. The 2010 super-flood, the most destructive in the country's history, affected about 20.1 million hectares across all provinces, claiming over 2,000 lives, displacing roughly 20 million people, and causing economic losses estimated at USD 43 billion, about 25% of annual GDP (Kirsch et al., 2012; Ashraf et al., 2013; Jamshed et al., 2020). Climate models indicate that human-induced warming increased the likelihood of the extreme rainfall that triggered the 2010 flood, though estimates vary across studies (Lau and Kim, 2012). The devastating 2022 monsoon floods, which covered about one-third of Pakistan's land area, killed more than 1,700 people and resulted in losses exceeding USD 30 billion (Hussain et al., 2023; Akhter, 2024; Mohsin, 2026). These events highlight how vulnerable the country's low-storage, flood-prone water systems are to more intense rainfall driven by climate change (NDMA, 2022; Ali et al., 2025). Climate projections consistently warn that flooding will intensify in Pakistan as temperatures rise, with RCP 8.5 simulations suggesting that floods that now occur once every 20 years could happen every 5 to 10 years by mid-century in the Jhelum and Chenab basins (Lutz et al., 2022).

At the same time, droughts are expected to become more frequent and severe, especially in southern and western Pakistan. For instance, projections for Balochistan and lower Sindh under RCP 4.5 indicate a 30-50% rise in the number of severe drought years by 2050 compared to the 1980-2010 baseline (Rehman et al., 2020; Nie et al., 2021). This combination of increased floods and droughts, often called the 'climate penalty, presents a significant challenge for infrastructure planning and water management, as the country faces more complex and unpredictable water-related risks.

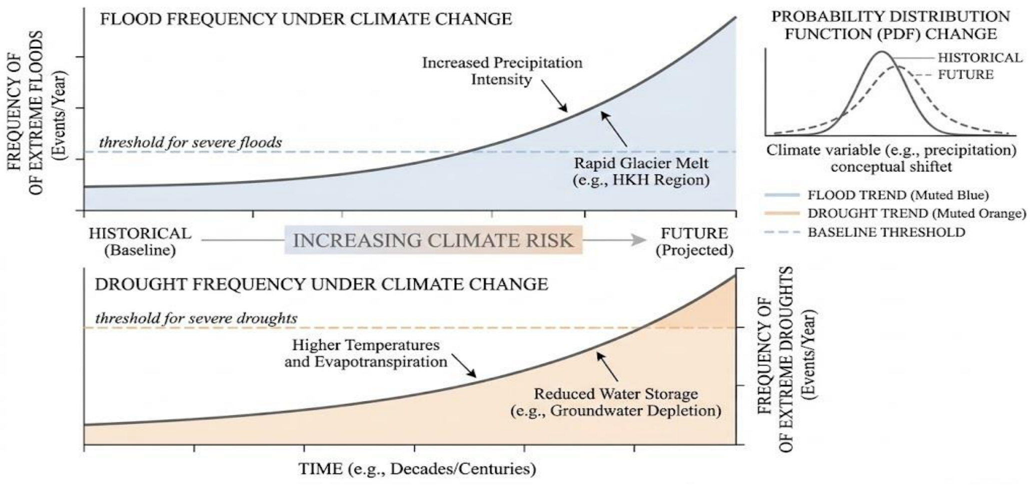

Figure 9: Increasing frequency of floods and droughts under climate change.

7.4 Implications for Irrigated Agriculture

A group researcher provided an in-depth look at the vital role of glacial meltwater in supporting agriculture across Asia (Biemans et al., 2019).

They estimated that glaciers provide meltwater for about 123 million hectares of irrigation in South and Central Asia, with Pakistan the most heavily reliant country.

According to their model under RCP 4.5, glacier meltwater contributions to the Indus irrigation system are expected to grow until around 2060, then decline by 25-35% relative to 2000 levels by 2100 (Winston, 2013; Habib, 2021). Under RCP 8.5, the decline is expected to be even sharper and occur sooner. Since Pakistan's food security relies heavily on irrigated wheat, rice, and sugarcane grown in the Indus Basin, these projections have significant implications for the country's food sovereignty, affecting not only water resources.

8. Future Outlook and Sustainability Pathways

8.1 Integrated Water Resources Management Framework

This review leads to a clear and hopeful conclusion: addressing Pakistan's water crisis requires more than isolated efforts in individual sectors.

Adopting an Integrated Water Resources Management (IWRM) approach, defined as a process that encourages the coordinated development and management of water, land, and related resources to boost economic and social well-being without harming vital ecosystems, provides a strong foundation for meaningful systemic change (Global Water Partnership, 2000). For IWRM to be truly effective in Pakistan, several crucial institutional steps are needed: (i) establishing a national water law that clearly defines and enforces water rights across all user groups and regions; (ii) empowering Water User Associations (WUAs) at the distributary and minor canal levels with genuine financial and operational independence; (iii) implementing volumetric pricing structures that reflect scarcity and promote efficiency without unfairly burdening smallholder farmers; and (iv) creating a reliable, data-sharing national water information system. While Pakistan has developed national water policies that outline many of these principles, there's still much progress to be made in turning these plans into action (National Water Policy, 2018; Mumtaz et al., 2020; Yasin et al., 2021).

8.2 Conjunctive Use of Surface Water and Groundwater

The most practical and immediate water management approach for Pakistan is to thoughtfully integrate surface water and groundwater use. Using groundwater to supplement canal supplies during low-flow periods and intentionally recharging aquifers with canal water during high-flow seasons can enhance water flexibility. Several pilot projects in Punjab have shown promising results in stabilizing groundwater levels while still supporting productive farming (Qureshi et al., 2010). To scale these successes, need to develop infrastructure for managed aquifer recharge (MAR) at a larger scale, update water-sharing rules to allow seasonal switching, and invest in advisory systems that help farmers make the best use of groundwater based on real-time canal conditions.

8.3 Remote Sensing and Technological Innovation

Remote sensing technologies offer exciting possibilities for improved water resources monitoring and management, especially in a country like Pakistan, where data can sometimes be limited. GRACE and GRACE-FO satellite gravimetry provide basin-wide estimates of groundwater storage change monthly, helping authorities detect early signs of depletion before it becomes a crisis, a capability that's incredibly valuable (MacDonald et al., 2016; Rodell et al., 2018). MODIS-derived actual evapotranspiration products, such as MOD16, show how water is used by crops across different areas, supporting smarter decisions on water allocation at the canal command level. Additionally, CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) offers a high-resolution (0.05°), near-real-time daily record of precipitation dating back to 1981, which is a fantastic resource for early flood warnings and monitoring agricultural droughts. On the ground, the increasing availability of affordable soil moisture sensors, satellite tools like Sentinel-1 and SMAP, and easy-to-use irrigation apps creates exciting opportunities to help farmers use water more efficiently without major investments in infrastructure. Still, to turn these possibilities into reality, there's a need for investments in digital infrastructure, farmer education programs, and data governance frameworks, areas that are still developing in Pakistan (Ali et al., 2026).

8.4 Infrastructure Development Priorities

Pakistan's urgent need for additional storage underscores the importance of investing in infrastructure (Rizwan, 2025). The Diamer-Bhasha Dam, under construction on the upper Indus as of the early 2020s, will add about 8.1 BCM of live storage and generate 4,500 MW of hydropower. This will greatly help manage seasonal water flow and ensure a more reliable supply (WAPDA, 2019). Still, building dams alone is not enough to fully address Pakistan's water issues; improving drainage and conveyance systems is equally vital, yet these have received less funding (Aijaz and Akhter, 2020; Lad and Jaybhaye, 2025). Upgrading high-loss earthen canals by lining them to reduce seepage, which is projected to recover 15-20 BCM per year across the system, offers a better return on investment for water security than investing the same amount in new storage for many canal areas (Kahlown and Kemper, 2005; Basharat, 2014).

8.5 Policy and Governance Reform

Addressing Pakistan's water crisis requires more than technical solutions; it's equally about effective governance. There is a need to strengthen enforcement of water allocation among provinces, especially under the 1991 Accord, by enhancing IRSA's role in transparency and oversight. Additionally, implementing sound groundwater management practices, such as mandatory well registration, accurate measurement of extraction, and fair pricing based on water depletion, is crucial to protecting aquifers. The Punjab Groundwater Governance Programme offers a promising start, but it needs to be strengthened and adopted more broadly. Another key step is to incorporate climate risk assessments into water infrastructure planning, ensuring that new projects account for future climate-related changes and avoid infrastructure that quickly becomes outdated or damaged. Beyond these efforts, international cooperation is vital, especially regarding the Indus Waters Treaty and discussions with Afghanistan about the Kabul River.

Since the Kabul River supplies a significant amount of water to the Indus system and upstream pressures from Afghanistan are increasing, it's important to work together to prevent unilateral diversions that could reduce water availability during dry seasons, especially for regions like the Peshawar Valley.

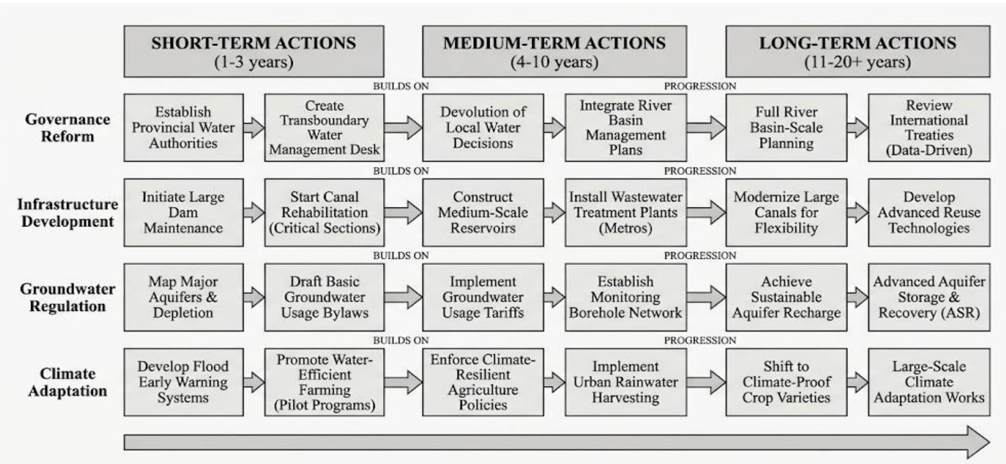

Figure 10: Strategic roadmap outlining short-, medium-, and long-term interventions for sustainable water governance.

9. Conclusion

This review provides an integrated historical, hydrological, and governance-based synthesis of Pakistan's water resources, with a particular focus on the Indus Basin. The evidence shows that Pakistan has moved from relative water abundance to acute water stress over a few decades, mainly due to rapid population growth, expanding irrigation demand, inefficient infrastructure, weak groundwater regulation, and increasing climate variability. Although the country still receives substantial renewable water, estimated at about 235-260 BCM annually, this resource base is under severe pressure from over-withdrawal, seasonal mismatch between supply and demand, and dependence on non-renewable groundwater in heavily cultivated regions such as Punjab.

The cryosphere remains a critical component of Pakistan's water system, supplying a large share of summer river flow through snow and glacier melt. However, this natural buffer is highly vulnerable to warming, with glaciers outside the Karakoram already showing clear signs of retreat. At the same time, climate change is intensifying hydroclimatic extremes, including floods, droughts, and rainfall variability, which further complicate water management across the basin. These changes are not spatially uniform; rather, they create distinct provincial water challenges. Punjab is characterized by groundwater depletion; Sindh by salinity, drainage failure, and reduced downstream flows; Khyber Pakhtunkhwa by flood- and glacier-related hazards; and Balochistan by chronic scarcity and aquifer collapse. This diversity demonstrates that a single national response is insufficient and that province-specific strategies are essential.

The findings also highlight that Pakistan's water crisis is not solely a problem of physical scarcity but also one of governance, institutional fragmentation, and low system efficiency. Canal losses remain high, storage capacity is limited, and groundwater extraction continues with inadequate monitoring or pricing mechanisms. To address these challenges, Pakistan urgently needs an integrated water resources management framework that links surface water, groundwater, and cryosphere planning. Priority actions should include strengthening groundwater laws, improving irrigation efficiency, expanding managed aquifer recharge, modernizing canal systems, and using remote sensing tools such as GRACE, MODIS, and CHIRPS for national-scale monitoring. In addition, stronger interprovincial coordination, transparent allocation mechanisms, and climate-informed infrastructure planning are necessary to build long-term resilience.

In conclusion, Pakistan's water future will depend on whether science-based governance and institutional reform can keep pace with growing hydrological stress. Without decisive action, continued depletion and climate pressure will deepen food insecurity, environmental degradation, and social inequality. However, with coordinated reform, technological monitoring, and integrated management, Pakistan still has the opportunity to shift from reactive crisis response toward a more sustainable and resilient water future.

References

Abd, U.R., Hannan, M., Mohammed, M. and Khan, N., 2025. Meta-Analysis of Alternate Wetting and Drying (AWD) Irrigation Effects on Methane and Nitrous Oxide Emissions Across Different Climates and Soil Types. European Journal of Ecology, Biology and Agriculture, 2(5), pp.181-200.

Abd, U.R., Hannan, M., Toqeer C. M., Farid. N., Suleman. M., Usman M.K., 2025. Arsenic Accumulation in Rice and Maize Crops and Associated Human Health Risks in Punjab, Pakistan. Int J Environ Sci Nat Res. 2025; 35(3): 556417.

Ahmad, M.U.D., Kirby, M., Islam, M.S., Hossain, M.J. and Islam, M.M., 2014. Groundwater use for irrigation and its productivity: status and opportunities for crop intensification for food security in Bangladesh. Water resources management, 28(5), pp.1415-1429.

Ahmed, K., Shahid, S., Harun, S. B., & Wang, X. J. (2016). Characterization of seasonal droughts in Balochistan Province, Pakistan. Stochastic environmental research and risk assessment, 30(2), 747-762.

Aijaz, A. and Akhter, M., 2020. From building dams to fetching water: Scales of politicization in the Indus Basin. Water, 12(5), p.1351.

Akhtar, M., 2024. Revisiting Climate Change as a Non-Traditional Security Threat to Pakistan: A Comparative Analysis (Master's thesis, National University of Sciences and Technology).

Ali, A., Ahmad, M., Nawaz, M. and Sattar, F., 2026. Spatial data infrastructure as the means to assemble geographic information necessary for effective agricultural policies in Pakistan. Information Development, 42(2), pp.805-827.

Ali, M., Hannan, M. and Ahmed, W., 2025. Cascading Risks and Adaptive Deficits: A Review of Climate Change Impacts on Pakistan's Water Security. European Journal of Theoretical and Applied Sciences, 3(6), 3-14.

Archer, D., 2003. Contrasting hydrological regimes in the upper Indus Basin. Journal of Hydrology, 274(1-4), pp.198-210.

Archer, D.R. and Fowler, H.J., 2004. Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications. Hydrology and Earth System Sciences, 8(1), pp.47-61.

Ashraf, A., Naz, R. and Roohi, R., 2012. Glacial lake outburst flood hazards in Hindukush, Karakoram and Himalayan Ranges of Pakistan: implications and risk analysis. Geomatics, Natural Hazards and Risk, 3(2), pp.113-132.

Ashraf, M., Arshad, A., Patel, P.M., Khan, A., Qamar, H., Siti-Sundari, R., Ghani, M.U., Amin, A. and Babar, J.R., 2021. Quantifying climate-induced drought risk to livelihood and mitigation actions in Balochistan. Natural Hazards, 109(3), pp.2127-2151.

Ashraf, S., Iftikhar, M., Shahbaz, B., Khan, G.A. and Luqman, M., 2013. IMPACTS OF FLOOD ON LIVELIHOODS AND FOOD SECURITY OF RURAL COMMUNITIES: A CASE STUDY OF SOUTHERN PUNJAB, PAKISTAN. Pakistan Journal of Agricultural Sciences, 50(4).

Basharat, M., 2014. INTERNATIONAL WATERLOGGING AND SALINITY RESEARCH INSTITUTE (IWASRI), LAHORE.

Biemans, H., Siderius, C., Lutz, A.F., Nepal, S., Ahmad, B., Hassan, T., von Bloh, W., Wijngaard, R.R., Wester, P., Shrestha, A.B. and Immerzeel, W.W., 2019. Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. Nature Sustainability, 2(7), pp.594-601.

Briscoe, J. and Qamar, U., 2006. Pakistan's water economy: Running dry. World Bank and Oxford University Press

Falkenmark, M., 1989. The massive water scarcity now threatening Africa: why isn't it being addressed?. Ambio, pp.112-118.

FAO AQUASTAT. (2021). Pakistan country profile. Food and Agriculture Organization of the United Nations. https://www.fao.org/aquastat/en/countries-and-basins/country-profiles/pakistan

Farinotti, D., Immerzeel, W.W., de Kok, R.J., Quincey, D.J. and Dehecq, A., 2020. Manifestations and mechanisms of the Karakoram glacier Anomaly. Nature geoscience, 13(1), pp.8-16.

Forsythe, N., Fowler, H.J., Li, X.F., Blenkinsop, S. and Pritchard, D., 2017. Karakoram temperature and glacial melt driven by regional atmospheric circulation variability. Nature Climate Change, 7(9), pp.664-670.

Global Water Partnership. (2000). Integrated water resources management. TAC Background Paper No. 4. GWP. https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/04-integrated-water-resources-management-2000-english.pdf

Habib, Z., 2021. Water availability, use and challenges in Pakistan-Water sector challenges in the Indus Basin and impact of climate change. Food & Agriculture Org.

Hannan, M., Ali, M., Lu, C. and Xu, J., 2026. Hydroclimatic Variability and Precipitation Extremes in Sindh under a Changing Climate. Advances in Environmental and Engineering Research, 7(1), pp.1-15.

Hannan, M., Dars, G.H., Ukasha, M. and Ansari, K., 2024. Spatiotemporal dynamics of groundwater storage in Pakistan from gravimetric observations. Journal of Hydrologic Engineering, 29(6), p.05024021.

Hannan, M., Lu, C., Waqas, M., Khan, A.U. and Liu, B., 2025. Regional heterogeneity in groundwater response driven by land-use transitions across Pakistan. Journal of Hydrology: Regional Studies, 62, p.102958.

Hewitt, K., 2005. The Karakoram anomaly? Glacier expansion and the 'elevation effect,'Karakoram Himalaya. Mountain Research and Development, 25(4), pp.332-340.

Hussain, M.A., Shuai, Z., Moawwez, M.A., Umar, T., Iqbal, M.R., Kamran, M. and Muneer, M., 2023. A review of spatial variations of multiple natural hazards and risk management strategies in Pakistan. Water, 15(3), p.407.

Hussain, S.S., Mudasser, M., Sheikh, M.M. and Manzoor, N., 2005. Climate change and variability in mountain regions of Pakistan implications for water and agriculture. Pakistan Journal of Meteorology, 2(4).

Hussain, T., Abbas, J., Li, B., Aman, J. and Ali, S., 2017. Natural resource management for the world's highest park: community attitudes on sustainability for central Karakoram national park, Pakistan. Sustainability, 9(6), p.972.

Ilyas, M., Ahmad, W., Khan, H., Yousaf, S., Yasir, M. and Khan, A., 2019. Environmental and health impacts of industrial wastewater effluents in Pakistan: a review. Reviews on environmental health, 34(2), pp.171-186.

Immerzeel, W.W., Van Beek, L.P. and Bierkens, M.F., 2010. Climate change will affect the Asian water towers. science, 328(5984), pp.1382-1385.

IPCC. 2021. Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Jamshed, A., Birkmann, J., McMillan, J.M., Rana, I.A. and Lauer, H., 2020. The impact of extreme floods on rural communities: evidence from Pakistan. In Climate Change, Hazards and Adaptation Options: Handling the Impacts of a Changing Climate (pp. 585-613). Cham: Springer International Publishing.

Jha, P.K., Tiwari, A., Gaire, N.P. and Shrestha, M.L., 2025. Climate Change and Forests in the Himalayas. In Himalayan Forests in a Changing World: Volume II: Climate Impacts, Biodiversity and Human Interactions (pp. 67-100). Singapore: Springer Nature Singapore.

Kahlown, M.A. and Kemper, W.D., 2005. Reducing water losses from channels using linings: costs and benefits in Pakistan. Agricultural water management, 74(1), pp.57-76.

Kalair, A.R., Abas, N., Hasan, Q.U., Kalair, E., Kalair, A. and Khan, N., 2019. Water, energy and food nexus of Indus Water Treaty: Water governance. Water-Energy Nexus, 2(1), pp.10-24.

Kenoyer, J.M., 1998. Ancient cities of the Indus valley civilization. Oxford University Press; American Institute of Pakistan Studies.

Kharya, A., Sachan, H.K., Tiwari, S.K., Rai, S.R., Joshi, D. and Dubey, V., 2025. Fluid Evolution of the Asian Continental Crust: Implication for Exhumation Tectonics of Trans Himalaya. HIMALAYAN GEOLOGY, 46(2).

Kirsch, T.D., Wadhwani, C., Sauer, L., Doocy, S. and Catlett, C., 2012. Impact of the 2010 Pakistan floods on rural and urban populations at six months. PLoS currents, 4, p.e4fdfb212d2432.

Lad, R.M. and Jaybhaye, R.G., 2025. Water politics in Pakistan: the internal and external dynamics. Water Policy, 27(1), pp.40-65.

Lau, W.K. and Kim, K.M., 2012. The 2010 Pakistan flood and Russian heat wave: Teleconnection of hydrometeorological extremes. Journal of Hydrometeorology, 13(1), pp.392-403.

Lightfoot, D.R., 1996. Syrian qanat Romani: history, ecology, abandonment. Journal of arid environments, 33(3), pp.321-336.

Lutz, A.F., Immerzeel, W.W., Shrestha, A.B. and Bierkens, M.F.P., 2014. Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. Nature Climate Change, 4(7), pp.587-592.

Lutz, A.F., Immerzeel, W.W., Siderius, C., Wijngaard, R.R., Nepal, S., Shrestha, A.B., Wester, P. and Biemans, H., 2022. South Asian agriculture increasingly dependent on meltwater and groundwater. Nature Climate Change, 12(6), pp.566-573.

MacDonald, A.M., Bonsor, H.C., Ahmed, K.M., Burgess, W.G., Basharat, M., Calow, R.C., Dixit, A., Foster, S.S.D., Gopal, K., Lapworth, D.J. and Lark, R.M., 2016. Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations. Nature Geoscience, 9(10), pp.762-766.

Mekonnen, M.M. and Hoekstra, A.Y., 2016. Four billion people facing severe water scarcity. Science advances, 2(2), p.e1500323.

Mohsin, M., 2026. Multisectoral Flood Resilience Framework for Pakistan: Insights from the Floods 2010 and 2022. In Flood Risk Reduction (pp. 311-338). Springer, Cham.

Mountain Research Initiative (MRI). (2015). Elevation-dependent warming in mountain regions of the world. Nature Climate Change, 5(5), 424–430. https://doi.org/10.1038/nclimate2563

Mumtaz, M., Sumra, K. and Khan, K., 2020. National water policy of Pakistan: A critical analysis. Journal of Managerial Sciences, 14(4).

Mustafa, U., Baig, M.B. and Straquadine, G.S., 2021. Impacts of climate change on agricultural sector of Pakistan: Status, consequences, and adoption options. In Emerging Challenges to Food Production and Security in Asia, Middle East, and Africa: Climate Risks and Resource Scarcity (pp. 43-64). Cham: Springer International Publishing.

Naseer, N., 2003. Analyzing the Effect Industrial Waste on River Ravi. Pakistan Journal of Applied Sciences, 3(1), pp.587-603.

NDMA (National Disaster Management Authority). 2022. Pakistan floods 2022: Situation report. Government of Pakistan. https://www.ndma.gov.pk

Nie, Y., Pritchard, H.D., Liu, Q., Hennig, T., Wang, W., Wang, X., Liu, S., Nepal, S., Samyn, D., Hewitt, K. and Chen, X., 2021. Glacial change and hydrological implications in the Himalaya and Karakoram. Nature reviews earth & environment, 2(2), pp.91-106.

Ostrom, E., 1990. Governing the commons: The evolution of institutions for collective action. Cambridge university press.

PCRWR (Pakistan Council of Research in Water Resources). 2017. National water quality status report 2016–2017. Government of Pakistan.

PCRWR. (Pakistan Council of Research in Water Resources). 2019. State of groundwater in Pakistan. Government of Pakistan.

Qureshi, A.S. and Perry, C., 2021. Managing water and salt for sustainable agriculture in the Indus Basin of Pakistan. Sustainability, 13(9), p.5303.

Qureshi, A.S., McCornick, P.G., Qadir, M. and Aslam, Z., 2008. Managing salinity and waterlogging in the Indus Basin of Pakistan. Agricultural water management, 95(1), pp.1-10.

Qureshi, A.S., McCornick, P.G., Sarwar, A. and Sharma, B.R., 2010. Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan. Water resources management, 24(8), pp.1551-1569.

Rahman, M.H.U., Ahmad, I., Ghaffar, A., Haider, G., Ahmad, A., Ahmad, B., Tariq, M., Nasim, W., Rasul, G., Fahad, S. and Ahmad, S., 2020. Climate resilient cotton production system: a case study in Pakistan. In Cotton production and uses: agronomy, crop protection, and postharvest technologies (pp. 447-484). Singapore: Springer Singapore.

Rasul, G., 2012. Climate data and modelling analysis of the Indus region. Pakistan Meteorological Department (PMD).

Rizwan, N., 2025. Exploring Country Platforms to Advance Pakistan's Energy Transition. Sustainable Development Policy Institute.

Rodell, M., Famiglietti, J.S., Wiese, D.N., Reager, J.T., Beaudoing, H.K., Landerer, F.W. and Lo, M.H., 2018. Emerging trends in global freshwater availability. Nature, 557(7707), pp.651-659.

Saddiqa, A., Batool, S., Gill, S.A. and Khan, A.J., 2022. Water governance and management in the 21st century: a case study of Pakistan. Pakistan Journal of Humanities and Social Sciences, 10(1), pp.29-42.

Salman, S.M. and Uprety, K., 2021. Conflict and cooperation on South Asia's international rivers: A legal perspective (Vol. 8). BRILL.

Smets, S.M.P., Kuper, M., Van Dam, J.C. and Feddes, R.A., 1997. Salinization and crop transpiration of irrigated fields in Pakistan's Punjab. Agricultural Water Management, 35(1-2), pp.43-60.

UNDP. 2013. Water governance in the Balochistan region of Pakistan: Situation analysis and reform options. UNDP Pakistan. https://www.undp.org/pakistan

United Nations. 2023. World water development report 2023: Partnerships and cooperation for water. UNESCO. https://www.unwater.org/publications/un-world-water-development-report-2023

WAPDA. 2018. Salinity and waterlogging survey report. Water and Power Development Authority, Government of Pakistan.

WAPDA. 2019. Tarbela 5th extension hydropower project: Environmental impact assessment. Water and Power Development Authority, Government of Pakistan.

Waqas, M., Hannan, M., Lu, C. and Rauf, A.U., Determining Flood Return Periods in River Swat Through Statistical Approaches. International Journal of Advanced Engineering and Management Research.

Winston, H.Y., 2013. The Indus basin of Pakistan: The impacts of climate risks on water and agriculture. World bank publications.

World Bank. 2022. Pakistan water security assessment. World Bank Group. https://openknowledge.worldbank.org

Wright Rita, P., 2010. The Ancient Indus: Urbanism, Economy, and Society. Cambridge University Press.

Yasin, H.Q., Breadsell, J. and Tahir, M.N., 2021. Climate-water governance: a systematic analysis of the water sector resilience and adaptation to combat climate change in Pakistan. Water Policy, 23(1), pp.1-35.