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Hydrological Extremes and Groundwater Sustainability Under Climate Variability and Anthropogenic Water Stress: A Systematic Review and Conceptual Framework

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ABSTRACT

Sustainability Groundwater in Lower Indus Basin aspiring to becomes more difficult to achieve from Climate Variability and Water Stress induced by human activities in Pakistan. This systematic study summarizes empirical science from hydrogeology, hydrogeochemistry, climatology, and agricultural engineering to assess how climatic extremes, unregulated groundwater extraction, and infrastructure breakdowns may have stressed groundwater in District Shaheed Benazirabad(SB) in the Province of Sindh in Pakistan. A onfined to non-confined district along the left bank of the Indus River is characterized by a hyper-arid to semi-arid climate, low relief (12.5 cm/km slope), and a shallow unconfined alluvial aquifer that is recharged predominantly through seepage from unlined canals. Hydroclimatic trend analysis has suggested increasing extremes, with the 2022 monsoon flood being 726% of normal rainfall in August, causing rapid water table rise and extended water logging. At the same time, the surface water shortage of 10–12% forces farmers to pump 4.3 to 6.0 BCM of groundwater a year, resulting in saline water upconing and quality decline. According to hydro-geochemical analysis, 55–80% of the groundwater samples tested do not meet World Health Organization (WHO) and Pakistan Standards and Quality Control Authority (PSQCA) drinking water guidelines for TDS (up to 6,050 mg/L), arsenic (up to 70 µg/L), and fecal coliform contamination 25 %. The "double threat" of waterlogging and secondary salinization impacts more than 60% of cultivated land, cutting cotton yields by as much as 50%. A six-pillar conceptual framework is introduced, including irrigation conveyance modernization, managed aquifer recharge, drainage re-engineering, solarized scavenger tubewells, decentralized water treatment, and institutional governance. Such an approach provides a replicable model for climate-adaptive aquifer management for at-risk alluvial basins in the Global South.

Introduction

Large-scale global climate variability and increasing anthropogenic water stress are key threats to the long-term ecological and hydrogeological stability of alluvial river basins throughout the global south. In the Lower Indus Basin (of Pakistan), the Shaheed

Benazirabad District (formerly Nawabshah District) is an important geographic focus of extreme hydrological vulnerability (Mitchell et al., 2021). This agricultural district, located on the left bank of the Indus River in central Sindh Province, is subject to extreme climate variability, from hyper-arid summer thermal stress to catastrophic monsoonal floods. The sub-surface hydrology of the district is inextricably linked to one of the largest surface water distribution systems in the world the Indus Basin Irrigation System (IBIS) through a complex system of unlined primary, secondary and tertiary canals (Lashari & Memon, 2024).

Over the past few decades, the combination of socio-ecological and climatic pressures has destabilized the regional water balance. Unlined irrigation conveyance through large channels, such as the Rohri and Nusrat canals, provides constant seepage to shallow unconfined aquifers (Khayyam, U., & Tariq et al., 2022). With the combination of flat natural topographic slopes with poor subsurface drainage systems design, this relentless artificial recharge has led to chronic waterlogging and secondary soil salinization a coupled ecological disaster historically known as the “twin menace”. At the same time, repeated surface water supply shortfalls at upstream barrage off-takes force farmers to resort to unregulated groundwater extraction to meet intensive cropping schedules (Hassan et al., 2025). This reliance on subterranean reserves is complicated by widespread water quality degradation characterized by elevated total dissolved solids (TDS), geogenic salinity, toxic heavy metal enrichment (most notably trace arsenic mobilization), and pervasive fecal coliform contamination (Nasir et al., 2021).

The vulnerability of Shaheed Benazirabad's groundwater system was exposed by the hydroclimatic shocks in the years 2010, 2011 and 2022. The 2022 monsoon deluge flooding devastated the agricultural fields, with surface floodwater held back for months by a non-performing drainage system. These microfloods modify shallow hydrodynamics, enhance rapid water table spikes, promote contaminant migration, and accelerate soil structure degradation (Wilderspin et al., 2019).

This World Review of Science, Technology and Sustainable Development paper draws on empirical works from hydrogeology, hydrogeochemistry, climatology and agricultural engineering to assess the compounded effects of climatic extremes, anthropogenic abstraction, and infrastructural failures on groundwater sustainability in District Shaheed Benazirabad. From this synthesis, a novel integrated conceptual framework is proposed to inform climate-adaptive aquifer governance, drainage re-engineering, and sustainable water resources management (Zubair, 2026).

Geographical, Demographic, and Hydrogeological Setting

The District Shaheed Benazirabad is situated in the central Sindh Province and lies in the central alluvial plain, with an area of 4,502 km², and it is located about 26°14′39″N lat 68°24′36″E long at an altitude of 31 m above the sea level. Once a part of Nawabshah District until it was renamed to honor former Prime Minister Benazir Bhutto in September 2008, administratively created during the British era on 1st November, 1912, the district also acts as key administrative and agricultural node (Haque & Butler, 2016).

It is divided into four sub-divisions (tehsils or talukas): Nawabshah, Daur, Sakrand, and Kazi Ahmed (previously Daulatpur). As per the 2023 population census of the country, the district has a population of 1,845,102 and the population density stands at 409.84 persons per km² (Jorgensen et al., 2024). The regional demography is largely rural(67.58%), where there is a total of 1,246,982 people in 91 revenue dehs and 59 Union Councils with 598,120 people living in urban attracted mainly by Nawabshah City. The totalarity is exposed by adult literacy gap estimated at 50.86%, indicative of large gender gap between males (61.07%) and females (40.29%) (Margat & Van der Gun, 2013).

The regional economy relies on irrigated agriculture, supported by a cultivated area exceeding 496,000 acres. The agricultural framework centers on high-water-demand cash crops, including sugarcane (producing approximately 1,956,240 metric tons annually), wheat (334,043 metric tons), and cotton (77,095 metric tons), along with commercial mango orchards (68,880 metric tons). Irrigation requirements are primarily sustained by surface water diversions from the Sukkur Barrage on the Indus River via the Rohri Canal and its major off-taking branches, such as the Nusrat Canal (Hynds et al., 2018).

Figure 1: Conceptual schematic of system dynamics governing groundwater, biosphere, lithosphere, and anthropogenic interactions under climate variability.

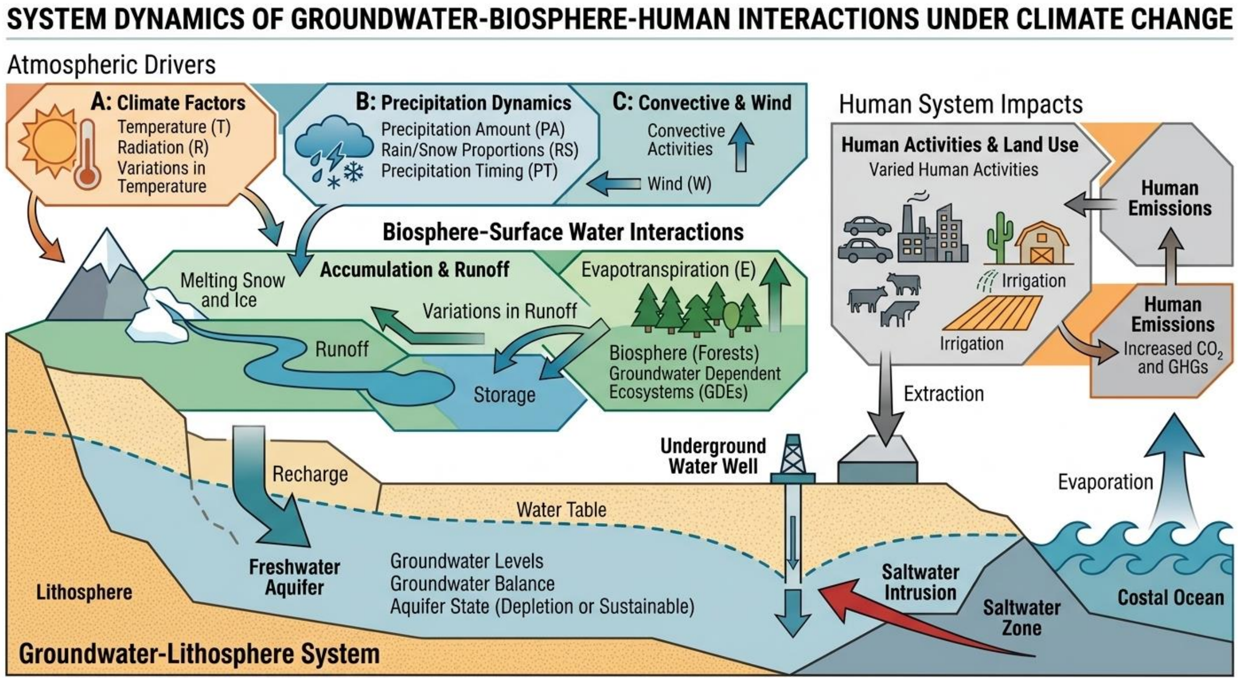

Table 1: Spatial, Demographic, and Land Use Characteristics of District Shaheed Benazirabad by Taluka

Parameter / Metric	Nawabshah Taluka	Daur Taluka	Sakrand Taluka	Kazi Ahmed Taluka	District Total / Average
Geographical Area (km^2)	435	2,210	885	972	4,502
Geographical Area (Acres)	108,652	538,549	196,608	--	~843,809
Cultivated Area (Acres)	95,681	250,887	150,164	--	>496,732
Forest Cover Area (Acres)	Negligible	Negligible	34,781	--	34,781
Total Population (2023 Census)	481,978	532,621	427,669	402,834	1,845,102
Population Density (ppl/km^2)	1,108.0	241.0	483.2	414.4	409.84
Literacy Rate (%)	62.44%	41.36%	52.84%	47.11%	50.86%
Administrative Units (Union Councils)	13	19	12	15	59

Hydrogeologically Shaheed Benazirabad is entrenched in the vast unconsolidated Quaternary alluvial deposits of Lower Indus Basin. The subsurface lithology is a complicated, highly heterogeneous intercalated sequence of fine-to-medium sand, silt and clay lenses laid down by ancient migratory streams of the Indus river system (Moeck et al., 2026). The major alluvial aquifer serves as regional unconfined to semi-unconfined groundwater system. The architecture of the sand-body based on core analysis informs the subsurface hydraulic properties: the horizontal hydraulic conductivity varies from <30 m/d in fine silt and clay rich layers to >90 m/d in coarse sand layers (Dressler et al., 2026).

Recharge to the shallow aquifer is by seepage from unlined canal beds, distributary channels, field application losses and localized riverine flooding. Decaying Areal Groundwater table depths-Strong spatial variabilities in static WTs are observed for the entire region: Near unlined main canals shallow GW levels are found in the range of (1.39 - 1.50) m b.g.l., Tail end farmland in east slopes are found with Deep static level with (15.4) m (Arnaud-Fassetta et al., 2010).

Hydroclimatic Regime and Climate Variability

District Shaheed Benazirabads climate is described as dry tropical continental with extreme temperature variations (comparable to hot desert climate but less dry to also comparable to cold semi-arid climate but less cold), with a very high rate of potential evapotranspiration and moody rainfall. Summers (between April and September) are vicious, with daily high temperatures invariably rising above 46 °C (115 °F) and soaring to 52.0 °C in Nawabshah City (one of the highest recorded temperatures in Asia). Winters are short and cool with coldest daily minimums occasionally dropping near freezing (Ljungqvist et al., 2016).

The inherent precipitation regime is one of sharp dryness. Long term Based on statistics of meteorological data from 1961 to 2011, the annual mean daily maximum single-day precipitation is 45.30 mm (±43.89" mm" standard deviation), which is followed by about 100 mm of cumulative precipitation as the annual mean (Carey et al., 2010). Temporally, the precipitation distribution is skewed; >80% of total annual precipitation falls within the summer monsoon season (July–September). Time-series models show good inter-annual variability (r^2=0.973 between consecutive regional rainfall time-series) which makes the area vulnerable to abrupt switches between severe drought and intense pluvial flooding (Pechlivanidis et al., 2017).

In recent decades, regional climate change has increased the frequency and severity of hydroclimatic disasters across central Sindh. Over the past fifteen years, three major flood disasters have impacted the region:

The 2010 Indus River Floods: Induced by catastrophic monsoonal cloudbursts across northern catchments, causing widespread riverine flooding, embankment breaches, and rural displacement across the Lower Indus plain (Arias et al., 2021).

The 2011 Sindh Pluvial Inundation: Driven by localized monsoonal storms that generated rainfall 248% above normal provincial baselines, flooding flat, low-lying agricultural zones.

The 2022 Monsoonal Deluge: Representing an extreme hydroclimatic event where July precipitation across Sindh exceeded normal monthly averages by 307%, followed by an August surge exceeding normal baselines by 726%. In the neighboring Padidan rain-gauge station, cumulative monsoonal rainfall reached a record high of 1,722 mm (Giorgi et al., 2014).

A comparison of historical precipitation benchmarks, extreme weather events, and associated impacts across the district and province is provided in Table 2.

Table 2: Historical Hydroclimatic Extremes and Precipitation Metrics in Sindh and Shaheed Benazirabad

Hydroclimatic Metric / Event	**Baseline / Normal Value**	**Observed Extreme Value**	**Hydrogeological & Agronomic Impact**
Mean Annual Daily Max Rainfall (1961–2011)	45.30 mm	256.30 mm (Single-day maximum)	Localized surface inundation, rapid groundwater table recharge
Maximum Summer Temperature	42.0°C – 44.0°C	52.0°C	Intense evapotranspiration, accelerated topsoil salinization
2011 Monsoon Anomaly (Sindh Province)	Historical Mean	+248% above seasonal normal	Widespread pluvial flooding, rapid water table rise
July 2022 Rainfall Anomaly (Sindh)	Monthly Average	+307% above seasonal normal	Vadose zone saturation, local drainage capacity failure
August 2022 Rainfall Anomaly (Sindh)	Monthly Average	+726% above seasonal normal	Prolonged agricultural flooding, elevated water tables
2022 Regional Seasonal Peak (Padidan)	~100–150 mm	1,722.0 mm	Extreme regional inundation, persistent waterlogging
Agricultural Inundation (2022 Floods)	--	78% of culturable land affected in Sindh	Inundation of 98% Rice, 81% Cotton, 71% Sugarcane

The hydrogeological connections between atmospheric extremes and subsurface responses are manifested through rapid infiltration that is limited by structural drainage elements. Level ground topography all over District Shaheed Benazirabad with an average gradient of (12.5 cm per kilometer or 8 inches per mile). As pluvial events of the magnitude recorded in 2022 take place, this absence of natural gradient obstructs gravity-driven surface runoff (PAGES et al., 2017).

Thus floodwaters stand trapped in farmlands for months. This prolonged surface ponding promotes vertical recharge to unconfined aquifers, elevating static water tables into crop root zones (<1.5" meters"). This rapid rise in water table mobilizes salts that have been accumulated in the unsaturated vadose zone, leading to a concentration of dissolved ions in the root zone while surface waters evaporate under hyper-arid thermal conditions (Beaugrand & Ibanez).

Subsurface Hydrodynamics: The Twin Menace of Waterlogging and Salinity

Waterlogging and secondary soil salinization are the 'twin threats' and are also a significant environmental barrier to agricultural production and groundwater management in Shaheed Benazirabad (Wang et al., 2025). Waterlogging is classified as the rise of static water tables to the primary root zone of field crops (<1.5" meters" depth), resulting in anaerobic soil conditions, interference with root respiration, and impairment of plant physiological activities. Secondary salinization is a result of evaporation of shallow water tables due to the surrounding heat, which brings dissolved sodium, chloride and sulfate ions to the surface soil (Wang et al., 2025).

The main cause of this underground water disequilibrium occurs on power of man: the historic construction of unlined surface canal networks and without sufficient subsurface-surface drainage conduits. Frequent seepage from the unlined main beds and banks of the Rohri and Nusrat canals replenishes the shallow alluvial aquifer. Since regional groundwater outflow is constrained by gentle land slopes (12.5 cm/km), subsurface recharge exceeds discharge and promotes a progressive water table rise (Kiran & Singh, 2021). For more than a decade, before targeted remediation measures were taken, around 60% of farmland in Shaheed Benazirabad had been categorized as waterlogged and saline, with over 35% of cultivated area experiencing static water tables rising to levels of <1.5" m" and 3.0" m" depth. The associated agronomic consequences are very serious: increases in soil EC (〚 "EC" 〛 _e) cause reduction of cotton crop yield by 10% at 5.5" dS/m", 25% at 7.4" dS/m", and 50% at 10.6" dS/m" (Alzraiee et al., 2013).

In response to this crisis, state agencies implemented a series of engineering interventions over the past half-century:

Salinity Control and Reclamation Projects (SCARP)

SCARP (the tubewell program under the barrage system) was launched in the late 20th century and was intended to reduce regional watertables by introducing massive high-capacity vertical tubewell networks that would lower groundwater by 1.5 m to 3.0 m over millions of hectares. While early interventions were deemed successful in bringing down shallow water tables and sodicity levels, the performance of SCARP deteriorated in the long term (Nagy, 2001). Analysis shows that SCARP interventions were largely rendered inoperable by energy supply disruptions; electricity grid disruptions and lack of power made up 43.8% of all downtime. Other constraints in operation were the prohibitive costs for operation and maintenance, corrosion of the pump impellers, and limitations of governance (Bokhari, 1980).

Hydrogeochemical Dynamics and Groundwater Quality Assessment

Groundwater conditions in District Shaheed Benazirabad are characterized by strong spatial and depth variability controlled by geogenic mineral dissolution, dilution by fresh canal seepage, and input of anthropogenic contaminants (Uddin et al., 2023). Aquifer units along large unlined drainage (the Indus River, Rohri Canal, and Nusrat Canal) are recharged by permanent freshwater inflows, and therefore maintain localized shallow low-salinity groundwater lenses available for use in agriculture and domestic work. Nonetheless, with the increase in horizontal distance from these recharge sources, as well as with the increase in sampling depth for beyond shallow aquifers (>15 meters), quality deteriorates to brackish and saline (Wagh et al., 2019).

The WQI-based ground water quality estimation in the district reveals that from 55% to 80% of the ground water does not fulfill the drinking water standards of WHO and PSQCA indicating its unsuitability for drinking purpose. Spatial interpolation of WQI categorizes 10.17% of the district area under excellent quality drinking water, 19.97% as good quality drinking water, 9.01% bad quality drinking water, 5.73% very bad quality drinking water, whereas 55.00% of the total (geographic) area has drinking water unfit for human consumption (Khan et al., 2016). The GOD index (Groundwater depth, Overburden lithology, Aquifer Media) and the DRASTIC model-based vulnerability mapping indicates about one-third of the district area is under high intrinsic aquifer vulnerability to contamination from the surface (Yang et al., 2016). Model validation using Receiver Operating Characteristic (ROC) curve analysis yielded an Area Under the Curve (AUC) of 0.95, confirming high predictive accuracy. Sensitivity analysis identified land slope as the most influential physical factor governing aquifer vulnerability, while the Topographic Wetness Index (TWI) exerted the least relative influence (Prasanna et al., 2011).

Figure 2: Systematic framework illustrating the cascading impacts of climate change, extreme weather, and environmental factors on population health outcomes and adaptation strategies.

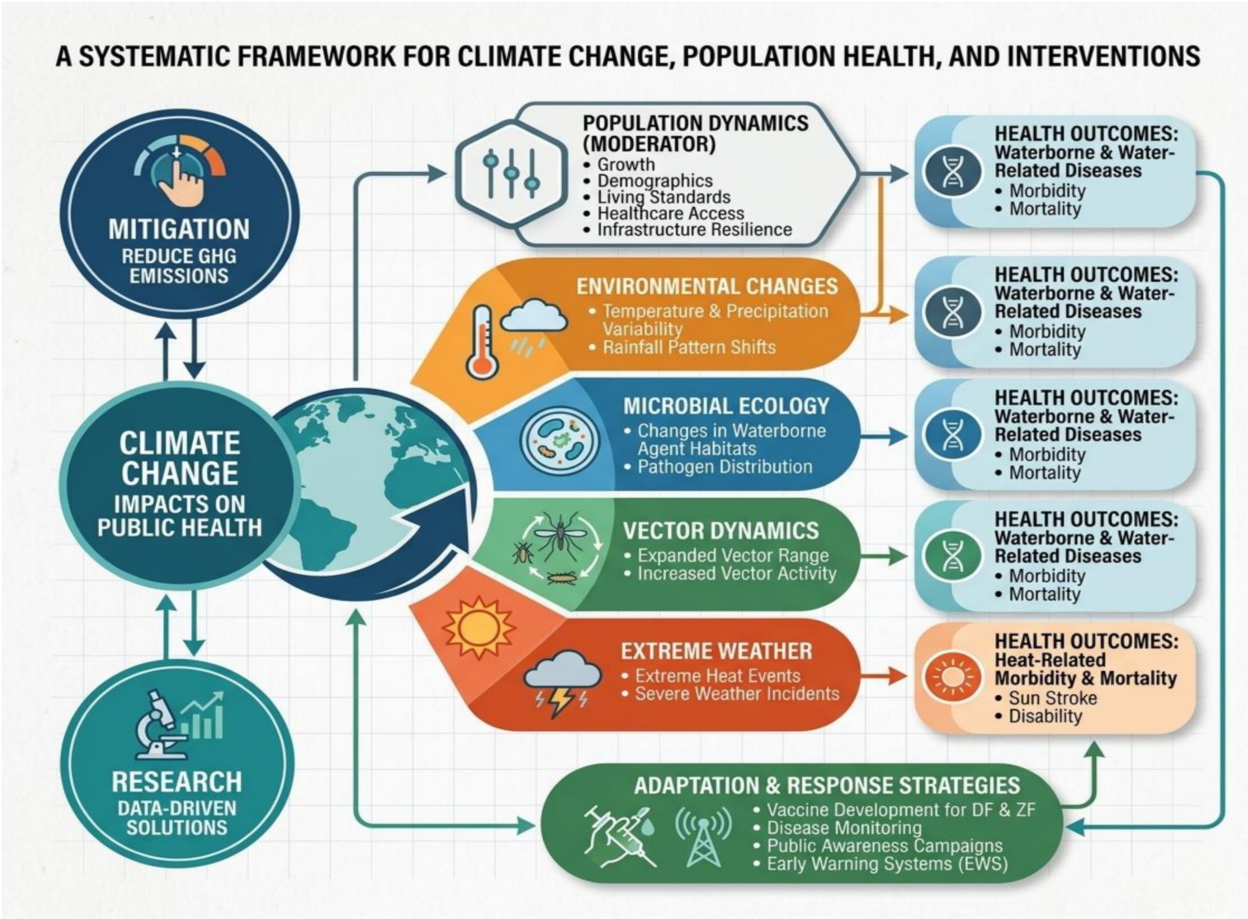

Table 3: Hydrogeochemical Parameters and Drinking Water Quality Standards in District Shaheed Benazirabad

Hydrochemical Parameter	Observed Concentration Range (District Data)	Mean / Average Value	WHO / PSQCA Permissible Limit	District Exceedance Rate & Health Implications
pH (Standard Units)	6.40 – 8.87	7.25 – 7.63	6.50 – 8.50	< 5% exceedance; generally within permissible neutral limits
Electrical Conductivity (EC)	310 – 2,148 µS/cm (up to 9,000 regional)	1,083 µS/cm	1,000 µS/cm	> 50% exceedance; reflects high dissolved ion contents
Total Dissolved Solids (TDS)	158 – 6,050 mg/L	1,182 – 1,273 mg/L	1,000 mg/L (500 desirable)	42.5% – 70% exceedance; imparts bitter taste, causes gastrointestinal distress
Total Hardness (as $CaCO_3$)	84 – 1,695 mg/L	384.3 mg/L	500 mg/L	32.5% – 82.5% classified as hard to very hard water
Sodium (Na^+)	31 – 1,725 mg/L	115.3 – 143.0 mg/L	200 mg/L	12.5% – 30% exceedance; contributes to hypertension risk
Calcium (Ca^{2+})	15 – 515 mg/L	83.2 mg/L	200 mg/L	15% – 25% exceedance; driven by calcite/gypsum dissolution
Magnesium (Mg^{2+})	13 – 430 mg/L	53.9 mg/L	150 mg/L	10% – 20% exceedance; contributes to total water hardness
Potassium (K^+)	1.0 – 92.0 mg/L	5.56 mg/L	12 mg/L (EC	< 5% exceedance; essential

			Standard)	electrolyte within safe bounds
Chloride (Cl^-)	14 – 1,852 mg/L	69.6 – 123.0 mg/L	250 mg/L	20% – 46% exceedance; indicates saline water mixing
Sulfate (SO_4^{2-})	11 – 2,170 mg/L	119.0 mg/L	250 mg/L	12.5% – 25% exceedance; causes cathartic effects at high levels
Bicarbonate (HCO_3^-)	61 – 815 mg/L	285.0 mg/L	No explicit WHO limit	Elevated in shallow fresh canal recharge zones
Nitrate (NO_3^-)	0.0 – 2.7 mg/L	0.66 mg/L	10 mg/L (as N)	0% exceedance; generally within safe limits
Arsenic (As)	2.0 – 70.0 µg/L	21.0 µg/L	10.0 µg/L	Critical local exceedance near riverine belts; carcinogen
Microbiological Pathogens	Positive / Negative	--	0 CFU / 100 mL	> 25% positive for fecal coliforms; causes waterborne disease

An analysis of specific geochemical parameters provides deeper insights into subsurface processes:

Salinity, Dissolved Solids, and Major Ion Chemistry

District TDS levels are highly variable ranging from 158 mg/L to 6,050 mg/L in the sampled wells, with mean values throughout the district having always been above 1,100" mg/L" Major cations show ⟦ "Na" ⟧ ^+>⟦ "Ca" ⟧ ^(2+)>⟦ "Mg" ⟧ ^(2+)>K^+ in order of relative abundance, while major anions are the presence of ⟦ "Cl" ⟧ ^- and ⟦ "SO" ⟧ _4^(2-), that is replaced by ⟦ "HCO" ⟧ _3^- for the most part at shallow recharge zones in canals (Ghoto et al., 2025). The majority of the groundwater (more than 82.5%) belongs to the category of hard to very hard water ("Hardness">300" mg/L" as CaCO_3), which is attributed to the natural dissolution of soil embedded calcite (CaCO_3) and gypsum (CaSO_4.2H_2O) minerals in the alluvial sediments (Jat Baloch et al., 2021).

Anthropogenic Water Stress and Agricultural Water Security

Then water resource is Iran is under the pressure of human activities in this case study of District Shaheed Benazirabad water. According to the 1991 Apportionment Water Accord, Sindh Province receives an annual surface water share of 48.76 MAF (60.15 BCM) from the Indus River System. Delivery deficits of 10% to 12% from statutory allocations are common at headworks on surface water releases for unlined main canals due to upstream operation constraints and fluctuation in river discharge, and conveyance losses in unlined canals (Falkenmark, 2013), but the norms are systematically different from this norm.

Farmers are heavily dependant on conjunctive water use to make up for surface water shortfalls, and to sustain rising cropping intensities that have climbed from 102.8% in 1960 to over 172% nowadays. Approximately 4.3 to 6.0 billion cubic metres (BCM) of groundwater is extracted annually by private or public tubewells across the Lower Indus plain. Groundwater extraction in Shaheed Benazirabad This groundwater withdrawal is largely unregulated by a centralized monitoring or spatial pumping regulations in Shaheed Benazirabad (Veettil & Mishra, 2018).

This unmanaged extraction creates several hydrogeological feedback loops:

Saline Water Upconing: In areas where shallow freshwater lenses (depths < 15 meters) overlie deeper, highly concentrated saline groundwater, intensive extraction by deep tubewells induces vertical upward migration (upconing) of saline water. This upconing salinizes shallow fresh zones, rendering pumped water unfit for both crop irrigation and domestic consumption (Ingrao et al., 2023).

Tail-End Irrigation Vulnerabilities: Agricultural areas situated at the tail ends of distributary canals experience persistent surface water delivery shortfalls. Farmers in these tail-end zones rely heavily on low-quality, brackish groundwater. Extended application of this saline water accelerates secondary soil salinization, leading to crop yield losses particularly for sensitive cash crops such as cotton and wheat (Lal, 2007).

Socio-Economic and Public Health Impacts: The consumption of untreated, highly saline groundwater containing elevated TDS, chloride, and bacterial pathogens contributes to gastrointestinal illness, diarrhea, and chronic health conditions (including renal stress and cardiovascular issues) across rural populations. Concurrently, agricultural yield reductions caused by soil salinity lower farm incomes, increasing rural poverty and forcing reliance on emergency state aid and public works employment (Spring, 2014).

Conceptual Framework for Sustainable Groundwater Management

An integrated conceptualization is needed to tackle the coupled problem of hydroclimatic extremes, waterlogging, salinization, and water quality deterioration in District Shaheed Benazirirbad. This conceptual approach integrates surface water hydrology, subsurface hydrogeochemistry, drainage engineering, and governance into a strategy for adaptive management (Wheater & Gober, 2015).

The conceptual framework is built upon six structural management pillars:

1. **Irrigation Conveyance Modernization and Seepage Reduction**

   Selective lining of primary canal sections (including targeted reaches of the Rohri and Nusrat canals) and distributary channels in high-permeability, shallow-waterlogged zones to limit unlined canal seepage. Reducing artificial recharge into shallow aquifers helps stabilize static water tables below the critical 1.5 m crop root zone threshold (Sharma et al., 2019).

2. **Managed Aquifer Recharge (MAR) and Monsoonal Skimming**

   Constructing dedicated Managed Aquifer Recharge (MAR) infrastructure, floodwater retention basins, and skimming wells along riverine zones. During high-discharge monsoon flood events (such as the 2022 floods), excess surface floodwaters can be captured, pre-filtered, and recharged into shallow aquifer zones. This approach mitigates surface flood ponding while replenishing fresh groundwater reserves (Schwartz & Liu, 2026).

3. **Drainage System Re-engineering and LBOD Restoration**

   Redesigning regional drainage infrastructure specifically addressing structural bottlenecks within the LBOD network to restore natural surface drainage pathways aligned with historical Indus and Hakro river channels. Re-establishing natural drainage paths prevents extended surface water ponding during monsoonal deluges, reducing topsoil salinization driven by evaporation (Muhammad et al., 2026).

4. **Expansion of Solarized Scavenger Tubewell Systems**

   Rehabilitating and expanding solar-powered scavenger tubewell networks across agricultural zones characterized by shallow fresh/saline water stratification. Equipping scavenger wells with dual-strainer extraction systems and variable-frequency drives prevents deep saline upconing while maintaining water tables at safe depths without relying on the electrical grid (Raut et al., 2025).

5. **Decentralized Smart Water Treatment Facilities**

   Deploying community-level, solar-powered Reverse Osmosis purification systems (such as PCRWR SDW-RO units) across rural Union Councils where WQI mapping indicates unfit drinking water quality. Integrating real-time online TDS and flow monitoring ensures long-term operational performance and safe drinking water supply (Cohen et al., 2025).

6. **Institutional Governance, Spatial Zoning, and Monitoring**

   Establishing a regional groundwater management framework responsible for enforcing extraction limits, mapping hydrogeochemical vulnerability using GIS-DRASTIC/GOD methods, and regulating deep tubewell construction in high-salinity upconing zones. Real-time telemetry monitoring networks should be implemented across all four talukas (Nawabshah, Daur, Sakrand, Kazi Ahmed) to track long-term hydrogeological trends (Liu et al., 2021).

Conclusion

This review reveals that the groundwater sustainability in the District Shaheed Benazirabad is at stake due to an interaction of hydroclimatic extremes, human-induced water stress, and infrastructural deficiencies. The district's level terrain, its unlined canal system, and reliance on conjunctive water use, have combined to induce a vicious cycle of waterlogging, salinization, and the impairment of groundwater quality. The twin menace covers more than 60 % of agricultural land and about 55–80 % of the groundwater samples has been found to be not suitable for drinking due to high salinity, arsenic, and microbial contamination. These pressures are being exacerbated by climate change, with the 2022 monsoon deluge being an extreme hydroclimatic event that undermined drainage infrastructure and accelerated contaminant migration. The collapse of past initiatives such as SCARP illustrates the urgency of developing adaptive, decentralized, and climate-resilient strategies. The comprehensive approach leading to a sustainable groundwater management path outlined with the six-pillar conceptual framework emerging from this review, that is conveyance modernization, managed aquifer recharge, drainage reformation, solar powered scavengers tubewells, decentralized treatment and institutional governance, is an ideal solution. This approach demands a level of coordination and leadership among federal, provincial, and local institutions that can organize actions backed by real-time monitoring systems and spatial zoning regulations. This review lays down an approach liable to be replicated in other fragile alluvial basins in the Global South that are subjected to similar hydroclimatic and anthropogenic drivers.

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