

Climate Change and Hydrological Vulnerability in Pakistan: Implications of Engineering and Technology Solutions on Achieving Water Security and United Nations Sustainable Development Goals (UNSDGs) by 2030

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ABSTRACT

Pakistan is vulnerable to the adverse impacts of climate change. Despite abundant water resources, it faces water scarcity due to the cumulative effects of climate change, inadequate storage infrastructure, inefficient water governance, and limited integration of engineering and technology to optimize water resources. A growing population and a lack of rationalization in sectoral water use are straining limited water resources. Irregular weather patterns that cause droughts and floods at regular intervals are a worrying development. The study examines the impact of climate actions on Pakistan's water security to achieve UNSDGs 6 and 13 by 2030. The study also examines the implications of Pakistan's transboundary water-sharing with India under the Indus Water Treaty (IWS), which India unilaterally placed in abeyance on 26 April 2025. The study provides empirical evidence of climate change's impact on water governance in Pakistan and offers viable solutions for efficient water governance through integrated, climate-smart water engineering that leverages existing infrastructure and develops forward-looking plans to address water management challenges sustainably.

1. Introduction

Pakistan is vulnerable to climate change [1]. According to the Global Climate Index, Pakistan ranks as the eighth most susceptible country [2]. This vulnerability is manifested in extreme weather patterns, such as the excessive floods witnessed in 2010 and from 2022 to last year, 2025. The floods have caused significant damage totalling PKR 3.2 trillion (US\$14.9 billion) and affected 30 million people [3]. Pakistan experiences regular, unpredictable floods and droughts, but over the last three years, both have occurred in the same year. Pakistan has about 7259 glaciers located in its northern parts. They cover 11780 km² and have a total ice volume of 2066 km³. Snow falls from December to February [4]. Climate change challenges the agricultural sector through rising temperatures, uncertain irrigation-water availability, variable monsoon patterns, increased water stress in arid and semi-arid regions, and extreme weather events such as floods, droughts, heat waves, cold waves, and cyclones [5]. Climate change has been linked to more frequent floods, necessitating new reservoirs to store and manage water resources for future consumption. Fig. 1 indicates Pakistan's climate vulnerability in South Asia.

Existing climate models have limitations in accurately representing seasonal variations, especially in Pakistan's

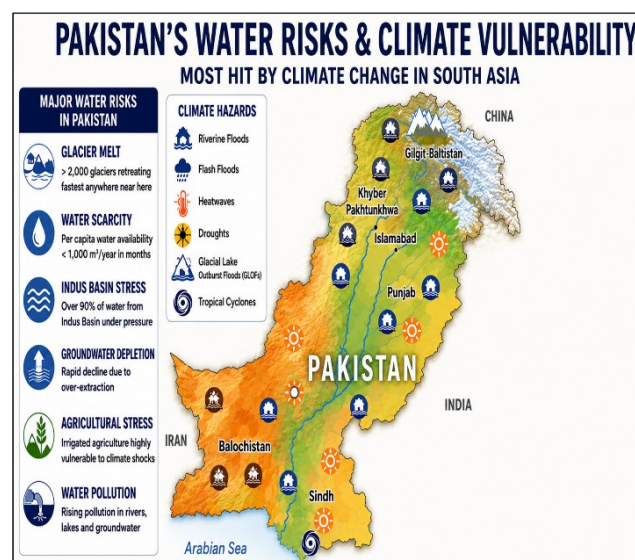


Fig. 1. Pakistan's climate vulnerability

northern regions [], which creates two significant issues as we confront climate change. First, floods and droughts are increasing. Second, existing reservoirs lack the capacity to store surplus water for use during dry seasons. The mountain regions of the Upper Indus Basin showed a statistically significant upward trend in average temperature, with increases of 1.5 °C in Baluchistan and 0.56 °C and 0.44 °C in Punjab and Sindh, respectively, from 1965 to 2023 [6]. Scientists

disagree on glacier retreat in the Himalaya-Karakoram-Hindukush regions, where yearly temperature trends rose notably across all three sites in the northwestern Himalayan region [7]. In contrast, summer temperatures decreased between 1961 and 2000, and glaciers in the Karakoram region increased [8]. Constant monitoring and regular investigations are necessary to provide a comprehensive update on the glacier's ecosystem in the Himalayan region, as it remains quite unexplored. Over the past 75 years, the country's per capita water availability has declined significantly, from 5,260 cubic meters to 908 cubic meters [9].

Without a proper water-saving policy, per-head water availability would drop to 860 cum by 2040 and further decrease to 500 cum after that [10]. As per world standards, per-head water availability is 1800 cum. When total water availability falls below 1000 cubic meters, a country is considered under water stress [11]. Pakistan currently ranks 23rd out of 167 countries facing water stress and is one of the 33 countries that will face a severe water shortage in the coming years [12]. Rising water demand is driven by urbanization, population growth, misuse of water resources, inefficient resource management, and the lack of a National Water Policy. Agriculture is the main driver of water stress, as it uses most of Pakistan's available water. Agriculture contributes 20% of Pakistan's GDP each year and employs approximately 40% of our workforce [13]. Water demand is projected to rise by 274 MAF by the year 2026. With supply staying at 191 MAF, we will have a deficit of 83 MAF [14]. Growing, unplanned cities have put water resources under great strain. While burgeoning real estate housing societies such as Bahria Town, Defense Housing, and other privileged societies have attracted strong customer interest, they have also added pressure on scarce water resources.

2. Literature Review

Water security is an evolving national security challenge for Pakistan [15] affecting human security. Pakistan's glaciers, particularly in the Himalayas and Karakoram ranges, are experiencing accelerated melting due to rising temperatures, which has severe consequences, including increased risk of glacial lake outburst resulting in excessive floods (GLOFs), which Pakistan has faced regularly over the last four years, and altered river flows affecting millions of people dependent on glacial meltwater for agriculture and drinking purposes [16]. Changes in precipitation patterns and glacial melt cause the unusual drought experienced during the same year from 2022 onwards to have significant implications for Pakistan's limited water resources and the exacerbation of water scarcity, particularly in arid and semi-arid regions, leading to reduced agricultural productivity, increased competition for water resources, and potential conflicts over water allocation among the provinces [17]. Climate change will bring more frequent floods, droughts, and heat waves, devastating people, property, crops, and incomes and increasing poverty and

hunger [18]. Due to climate change, Pakistan will suffer from reduced crop yields, shifting cropping patterns, more frequent pest outbreaks, and livestock losses, which can result in food insecurity [19]. Water shortages, floods, and environmental degradation from climate change are driving migration in Pakistan. Heat stress, disease, and food insecurity due to climate change have resulted in more heat strokes, water-related diseases, malnutrition, and mental disorders. These effects are more severe for vulnerable populations and increase health inequities. Climate change has also affected water quality in Pakistan, especially drinking water. Climate change will greatly challenge water governance in Pakistan by affecting water quantity, quality, and distribution. More research is needed on how climate change will affect water governance [20]. The literature review indicates that Pakistan has the most water-intensive economy globally, consuming the most water per unit of GDP and reflecting remarkably low productivity and efficiency [21].

Given that Pakistan allocates 93% of its freshwater resources to agriculture, it is imperative to improve the current efficiency rate, which stands at 50%. Scholarship also indicates that canal irrigation efficiency can be as low as 33%, meaning only 33% of the water discharged into canals reaches its intended destination [22]. Inadequate water reservoirs, ineffective water management in agriculture and households, limited wastewater recycling, and contaminated drinking water have become major health risks, creating human security challenges for Pakistan [23]. The transboundary water sharing between India and Pakistan has been firmly in place since the implementation of the Indus Water Treaty (IWT) in 1960, but during the recent conflict in May 2025, India has unilaterally put IWT in abeyance and is not ready to restore it, therefore multiplying Pakistan's water security challenges as a lower riparian country [24]. The Indus River System (IRS) serves as Pakistan's lifeline [25]. However, declining snowfall in the Himalayas and Karakoram Mountains, population growth, unsustainable agricultural practices, and asymmetry in sectoral water distribution [26] have exacerbated Pakistan's water security issues [27].

The current literature review indicates that unchecked urbanization, the negative impacts of climate change, weak governance, and inefficient water management have contributed to water scarcity and unprecedented flooding, including urban flooding in 2025 [28]. Hydrological studies and remote sensing indicate excessive reduction in groundwater levels and land subsidence in megacities like Lahore and Islamabad, which is directly linked to excessive groundwater extraction, minimal recharge by regulating rainwater into pre-planned channels, and unchecked installation of tubewells, especially after the government has deregulated and facilitated solar usage for tubewells [29]. Such unregulated trends have caused water depletion and contamination of water sources, creating public health issues that undermine urban resilience efforts [30]. An innovative approach

to water conservation and public awareness is to install smart meters, billed regularly like other utilities, to inculcate a sense of water conservation among the population, especially in urban centers, where population growth has created unprecedented stress on limited water sources. Pakistan's water security warrants an integrated water management system to achieve sustainable water management in the medium- to long-term [31]. Pakistan's existing water governance model needs refinement to address the evolving challenges of climate change, urbanization, and sustainable water management [32] for achieving UNSDG 6 and 13 by 2030. Pakistan's water insecurity warrants adopting smart technologies for water conservation, distribution, and quality [33]. The most important gap in the existing scholarship is the engineering and technological challenges in water storage and distribution, especially in Sindh, a lower-riparian province. Therefore, this study involves an in-depth investigation of three reservoirs in Sindh from an engineering and technological perspective.

3. Research Methodology

The study involves a three-stage process. In the first stage, the study examines the implications of climate change for water security by investigating precipitation patterns and drought across Pakistan from 2020 onwards. The second stage examines water security in Sindh province by investigating drought and precipitation in Sindh from 2020 to 2025 using GIS mapping methods. In the third stage, the study investigates engineering problems at three aging reservoirs in Sindh to assess capacity, storage, and outflow. The study proposes integrated climate-smart engineering solutions to optimize water resources in Sindh and ensure sustainable water security. The study uses a mixed-methods approach to examine the relationship between climate change and water security in Pakistan. Fig. 2 outlines the overall methodological process, integrating hydrological engineering, climate resilience, adaptation, and policy analysis to provide a rigorous investigation and results.

3.1 Research Design

The research used an explanatory mixed-methods design, combining quantitative hydrological analysis with qualitative policy and governance assessments to integrate empirical data with institutional evaluations. The quantitative method examines precipitation, glacial melt, river flow variations, groundwater depletion, and reservoir storage. The qualitative method examines institutional resilience, climate adaptation, and policies aimed at achieving the SDGs. The research design follows the concept of IWRM (Integrated Water Resource Management). The process involves robust infrastructure and sustainable water management, incorporating linkages among climate change, water security, available infrastructure, and social vulnerability. Figs. 3 to 5 illustrate different components of the research design

and variables.



Fig. 2. Overall research framework

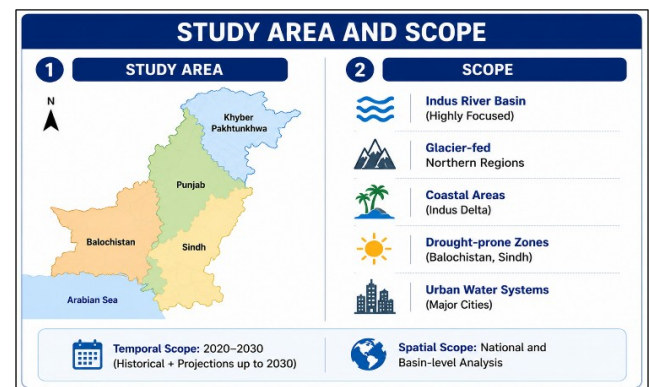


Fig. 3. Study area and scope

KEY VARIABLES AND INDICATORS		
DIMENSION	INDICATORS (EXAMPLES)	MEASUREMENT UNIT
CLIMATE	Temperature Anomaly, Rainfall Variability, Evapotranspiration, Extreme Events	Trend Analysis, °C, mm, Frequency
WATER RESOURCES	River Discharge, Water Availability per Capita, Groundwater Levels, Drought Index	Hydrological Modeling, Index Scores
INFRASTRUCTURE	Storage Capacity, Infrastructure Risk, Condition Index	Engineering Assessment, Performance Metrics
ADAPTATION	Irrigation Efficiency, Water Use Technology, Early Warning Systems	Adoption Rate, %, System Coverage
SDG IMPACT	SDG 6, 13, 11, 2 Index, Goal Interlinking, Risk, Climate Action, Urban Sustainability	SDG Indicator Score, Impact Assessment

Fig. 4. Key variables and indicators

3.2 Data Collection

Primary data were collected through field visits to three barrages in Sindh province and technical consultations with officials from the canal and irrigation departments to obtain information on the engineering problems of

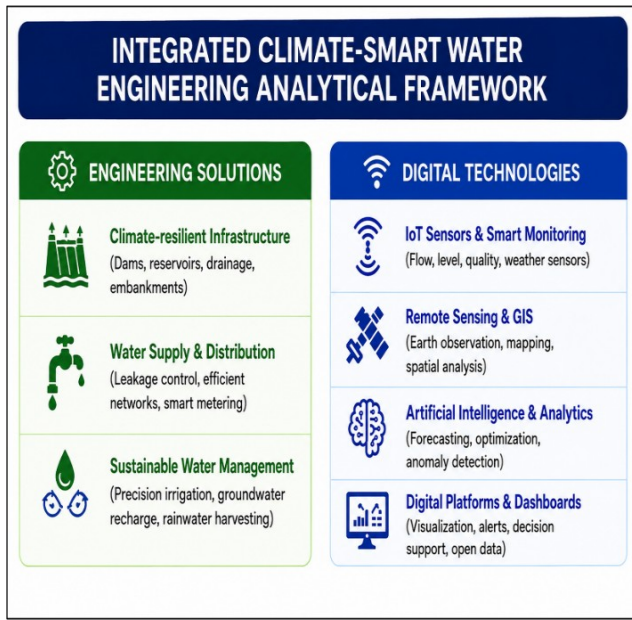


Fig. 5. Engineering Analytical Framework

these water reservoirs. Secondary data were collected from meteorological, hydrological, engineering, policy, and scientific sources.

3.3 Hydrological Vulnerability Assessment

This study investigated the climate-induced vulnerability of three water reservoirs in Sindh: Guddu, Sukkur, and Kotri. Additionally, the examination considered climatic variation patterns in Sindh from 2020 to 2025 to identify rainfall, drought, and river discharge at the three reservoirs, sedimentation, and seasonal water availability impacting agriculture and other water uses in Sindh, as a lower riparian. Barrage inflows, outflows, and differentials were obtained to determine stress levels, water shortages, and flood exposure. The findings supported the infrastructure resilience and water security challenges under varying climatic patterns.

3.4 GIS Mapping Process

This process helped in investigating the spatial distribution of drought and rainfall patterns in Sindh from 2020 to 2025. We generated a geospatial database by integrating district alignments, hydrological features, drought and rainfall indicators, and remote sensing data. Overlay analysis and graduated colour schemes were applied in generating thematic maps. We classified drought intensity from normal to extreme, and categorized rainfall data as very low, low, moderate, high, and very high.

3.5 Engineering and Technological Analysis/ Solutions

This assessed how we can build a stronger, more resilient approach to water management. This included looking at Barrages, Regulators, Drains, embankments, and water storage and distribution systems. We also explored technologies such as IoT sensors, Telemetry, Remote Sensing, GIS, AI, and digital platforms. These technologies enable better measurements of flows, Flood Prediction, Drought prediction, Leakage prediction,

and Predictive Maintenance. The study assessed all solutions for technical feasibility and cost. The study also focused on Sedimentation control, Condition Monitoring, Efficient Irrigation, and Prediction to improve water security under uncertain climates.

3.6 Mathematical Probability Distribution Model

We used a rigorous approach to calculating return periods for extreme events. We selected mathematical and statistical methods to estimate probabilities for zone creation and determine which rainfall patterns we could predict. We used L-Moment Estimators and the Method of Moments (MOM) to estimate distribution-model parameters. We then tested our distribution models using Goodness-of-Fit (GoF) methods. The details are described below.

Sample mean

$$X_{avg} = \frac{\sum X_i}{n} \quad (1)$$

Standard deviation

$$\sigma = \sqrt{\frac{1}{n-1} \sum (X_i - X_{avg})^2} \quad (2)$$

Skewness coefficient

$$\gamma = \frac{n \sum (X - X_{avg})^3}{(n-1)(n-2)S^3} \quad (3)$$

In the formulas above, readings are denoted by N, the frequency of observations by I, and the order of the observational data by Xi.

The normal distribution (N), also known as the Gaussian distribution, helps identify annual rainfall patterns

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp \left[-\frac{(x - \mu)^2}{2\sigma^2} \right] \quad (4)$$

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{\infty} \left(\exp \left[-\frac{(x - \mu)^2}{2\sigma^2} \right] \right) dx \quad (5)$$

The parameter of the normal distribution “x” is computed using the MOM.

$$\sigma_Y = \sqrt{\ln \left(1 + \frac{\sigma_X^2}{\mu_X^2} \right)} \quad (6)$$

$$\mu_Y = \ln(\mu_X) - \frac{1}{2} \sigma_Y^2 \quad (7)$$

For hydraulic frequency and function analysis, the Pearson type-III (P3) distribution is an ideal choice, as given by the formulas below.

$$f(x) = \frac{1}{|\alpha| \Gamma(\beta)} \left[\left(\frac{x - \zeta}{\alpha} \right)^{\beta-1} \right] \exp \left[- \left(\frac{x - \zeta}{\alpha} \right) \right] \quad (8)$$

$$F(x) = \frac{1}{|\alpha| \Gamma(\beta)} \int_{\zeta}^x \left[\left(\frac{x - \zeta}{\alpha} \right)^{\beta-1} \right] \times \exp \left[- \left(\frac{x - \zeta}{\alpha} \right) \right] dx \quad (9)$$

$$f(x) = \frac{1}{|\alpha| x \Gamma(\beta)} \left[\left(\frac{\ln(x) - \zeta}{\alpha} \right)^{\beta-1} \right] \times \exp \left[- \left(\frac{\ln(x) - \zeta}{\alpha} \right) \right] \quad (10)$$

Log Pearson type-III (LP3) uses the logarithms of the variables, as given by the formula below.

$$F(x) = \frac{1}{|\alpha| \Gamma(\beta)} \int_0^x \frac{1}{x} \left[\left(\frac{\ln(x) - \zeta}{\alpha} \right)^{\beta-1} \right] \times \exp \left[- \left(\frac{\ln(x) - \zeta}{\alpha} \right) \right] dx \quad (11)$$

The Gumbel distribution (GUM) helps in the calculation of datasets with maximum value or discharge in the case of water calculation

$$f(x) = \left(\frac{1}{\alpha} \right) \exp \left[- \left(\frac{x - \beta}{\alpha} \right) - \exp \left(- \left(\frac{x - \beta}{\alpha} \right) \right) \right] \quad (12)$$

$$F(x) = \exp \left[- \exp \left(- \frac{x - \beta}{\alpha} \right) \right] \quad (13)$$

By applying a suitable fitness test, the system validates the distribution model using a three-stage methodology to assess normality from multiple perspectives. First, the system uses graphical approaches, including Q-Q plots, histograms, and box plots. Next, validation uses numerical methods, including examining skewness and kurtosis indices and applying the normality tests shown below.

$$S_n(x) = 0; \text{ if } X < X_1 \quad (14)$$

$$S_n(x) = 1; \text{ if } X > X_n \quad (15)$$

$$D_n = \max |F_x(x) - S_n(x)| \quad (16)$$

$$P(D_n \leq D_n^\alpha) = 1 - \alpha \quad (17)$$

RMSE denotes root mean square error, which indicates the best-fit model of the variation and highlights the standard deviation of the projected error.

$$RMSE = \sqrt{\frac{1}{n} \sum (x_i - X)^2} \quad (18)$$

The return period is vital for investigating extreme flood events. This computation helps estimate the likelihood of occurrence and provides a temporal window for implementing measures to manage adverse-impact floods.

$$T = \frac{1}{1 - P(x \leq x_T)} \quad (19)$$

3.7 Climate Adaptation and Resilience Analysis

The process examined adaptation mechanisms across both structural and non-structural aspects. Structural aspects included available and projected water storage facilities, canal lining, drip irrigation, groundwater use, recharge processes, and drainage systems. Non-structural aspects included integrated water resources management, digital monitoring, community adaptation, and climate resilience processes.

3.8 Hydrological Climate Analysis

A quantitative investigation using time-series statistical methods examined variations in precipitation patterns, groundwater depletion, and water availability during the acute agricultural seasons. Climate trend analysis

helped develop a comprehensive climate map and examine climatic vulnerabilities that affect water security in Pakistan. The study integrated monitoring stations from the existing meteorological department to prepare datasets, which were processed using ANOVA and SPSS, with the Dunnett T3 test for multiple comparisons at $\alpha = 0.05$. ANOVA is rigorous and efficient, minimizes the risk of error, and provides a comprehensive comparison across multiple groups. Moreover, ANOVA helps determine whether differences in water governance efficiency among the cities are statistically significant. Figures 8 and 9 explain the ANOVA and SPSS processes, respectively, and Figure 10 shows the meteorological stations used to monitor precipitation patterns and amounts.



Fig. 6. Meteorological monitoring stations

4. Results and Discussion

4.1 Climate Change Vulnerabilities

The Global Climate Index (GCI) for 2025 shows that Pakistan is highly vulnerable to climate-related hazards, ranking 8th in the vulnerability index [34] and facing heatwaves, drought, and flooding. As a result, Pakistan's water supplies are affected by variations in weather patterns. Fig. 7 and Table 2 present the mean rainfall, derived from 25 years of statistical analysis using the Mean and Median process at the observation points and ANOVA in SPSS.

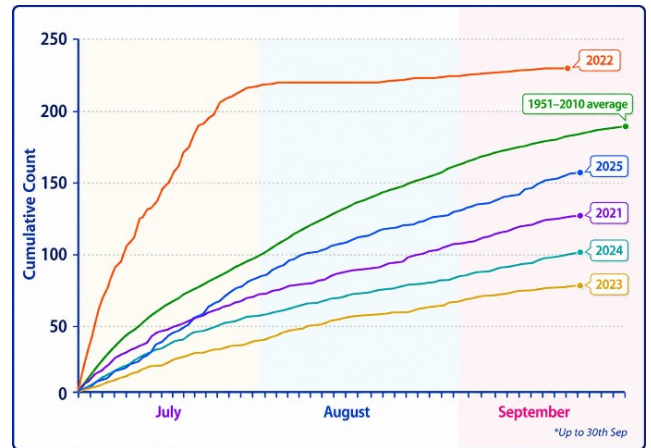


Fig. 7. ANOVA results of precipitation pattern

catastrophic for flooding due to heavy rainfall.

4.2 Probability Distribution Analysis

To make a strong case for climate change and its implications for extreme weather patterns in Pakistan, a comprehensive analysis of mathematical models and SPSS-generated precipitation patterns and drought hotspots, along with their impacts, is presented in Table 3, and Fig. 8.

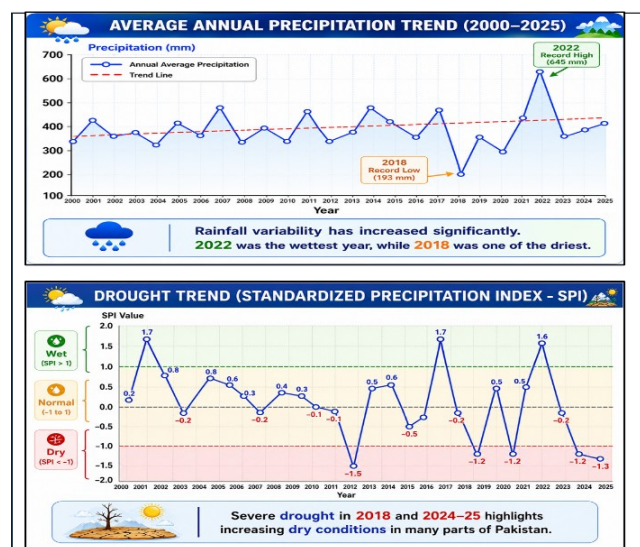


Fig. 8. Cumulative precipitation and drought trends in Pakistan from 2000 to 2025

4.3 GIS Mapping of Precipitation and Drought Patterns of Sindh Province

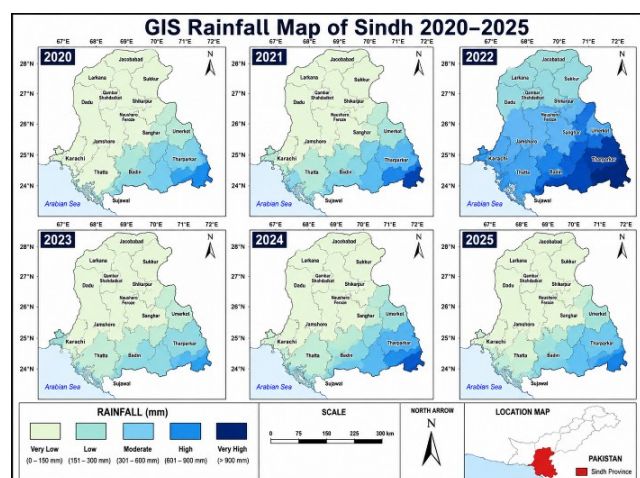


Fig. 9. GIS map of precipitation trends in Sindh from 2020 to 2025, with provincial bars

Fig. 9 shows a GIS-based map of Sindh’s rainfall distribution for 2020–2025, organized into six annual panels for comparison. The color scale identifies rainfall-deficit and substantially wetter zones, ranging from very low to very high. Due to their arid climate and reliance on Indus-based irrigation, northern and north-western districts such as Jacobabad, Larkana, Dadu, and Sukkur typically receive minimal rainfall. In contrast, districts in the southeast, such as Tharparkar, Umerkot, Mirpurkhas, Badin, Thatta, and Sujawal, receive somewhat more rainfall. The wettest year, 2022, emphasizes Sindh’s vulnerability to monsoon unpredictability and flood risk.

Fig. 10 shows a GIS-based map of Sindh’s drought

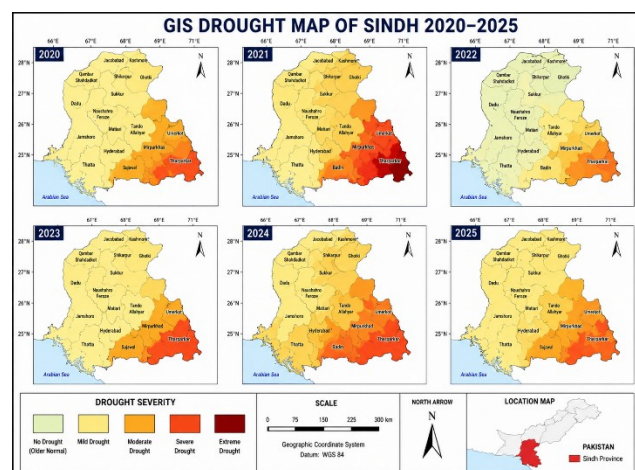


Fig. 10. GIS map showing drought severity trends in Sindh from 2020 to 2025

intensity for the years 2020–2025. With light green denoting no drought, yellow denoting mild drought, orange denoting moderate drought, dark orange denoting severe drought, and dark red denoting extreme drought, the graduated color scheme shows drought intensity from near-normal to extreme. The map shows that Sindh’s drought conditions are not evenly distributed. Due to low rainfall, fragile groundwater, and restricted surface water supply, districts in the east and southeast, especially Tharparkar, Umerkot, Mirpurkhas, Badin, Sanghar, and adjacent semi-arid areas, are more vulnerable. Districts closer to the Indus River on the western side of the province, or in the middle, tend to have less drought. Drought increased slightly in 2022, but 2021 appears to have been hit hardest. Overall, this map can support climate change mitigation plans, water security, and SDG 6 policy actions.

4.4 Water Sharing with India and Implications of Indus Water Treaty (IWT)

The Indus Water Treaty (1960) divides water sharing between Pakistan and India. The World Bank brokered it. The three eastern rivers go to India: the Ravi, Beas, and Sutlej. The three western rivers go to Pakistan: the Indus, Jhelum, and Chenab. India said in 2025 that it would place the treaty in “abeyance” after the five-day war. Pakistan has disputed this, saying it violates the treaty and international law. The evolving situation has negative consequences for agriculture, water security, regional stability, and crisis management between two nuclear-armed neighbors. Pakistan has rejected India’s statement about suspending the Indus Water Treaty. Pakistan has used every available avenue through international bodies and countries to restore the Indus Water Treaty to its pre-May 2025 status.

Pakistan has only 3 dams that can store water. These dams are not nearly enough for Pakistan. These include Mangla Dam (built in 1967), Chashma Reservoir (built in 1971), and Tarbela Dam (built in 1978). These are some of Pakistan’s largest dams. They were initially built with a combined capacity of 15.75 million acre-feet (MAF). However, due to sedimentation, the effective capacity of these reservoirs has decreased to



Fig. 11. Transboundary water sharing between India and Pakistan

13.1 million acre-feet (MAF), providing storage for only 30 days, well below the globally accepted standard of at least 120 days. Additionally, poor maintenance has caused seepage in the canals and link canals. The farmers mostly rely on conventional farming methods and flood irrigation rather than adopting drip irrigation. Excessive water use has led to water exhaustion for agriculture, especially during non-monsoon periods. India-Pakistan water sharing was formalized by the Indus Water Treaty (IWT) on September 19, 1960, in which India was granted rights to two rivers located in the eastern region, specifically Beas/Sutlej and Ravi, and Pakistan was granted rights to three rivers situated in the western areas, Jhelum, Chenab, and Indus. Although there have been three major wars and two instances of standoff with India, the Indus Water Treaty (IWT) has prevailed, while May 2025 was destabilizing in the sense that India unilaterally held the IWT in abeyance but let the eastern rivers flow into Pakistan during an unprecedented monsoon in 2025, causing exceptional floods never witnessed before in the last four decades. Despite concerns over the dam construction on the river flow in Indian Occupied Kashmir by India, it has largely achieved success. Fig. 11 shows the distribution of rivers outlined in the Indus Water Treaty (IWT) between India and Pakistan.

4.5 Engineering and Technology Analysis of Sindh's Reservoirs

Engineering problems at Guddu Barrage include decaying mechanical systems, sedimentation, hydraulic stress, and aging structural elements. Corrosion, abrasion, seepage, and fatigue can affect its gates, hoisting equipment, piers, aprons, and canal head regulators. A heavy sediment load impacts canal distribution and reduces flow efficiency. During floods and other major hydrological events, local scour, riverbank erosion, weak telemetry, limited automation, and inadequate maintenance further reduce operational reliability and climate resilience.

Problems at the Sukkur Barrage have developed because of the structure's age, silt load, hydraulic overloading, and changing climatic conditions. The concrete piers, arches, gates, downstream floor, canal head regulators, and mechanical working parts of the barrage suffer

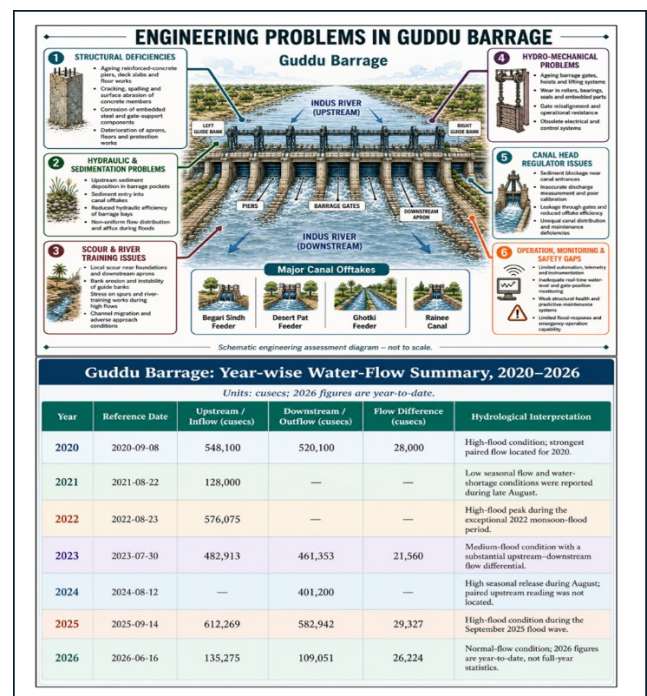


Fig. 12. Engineering problems of Guddu Barrage

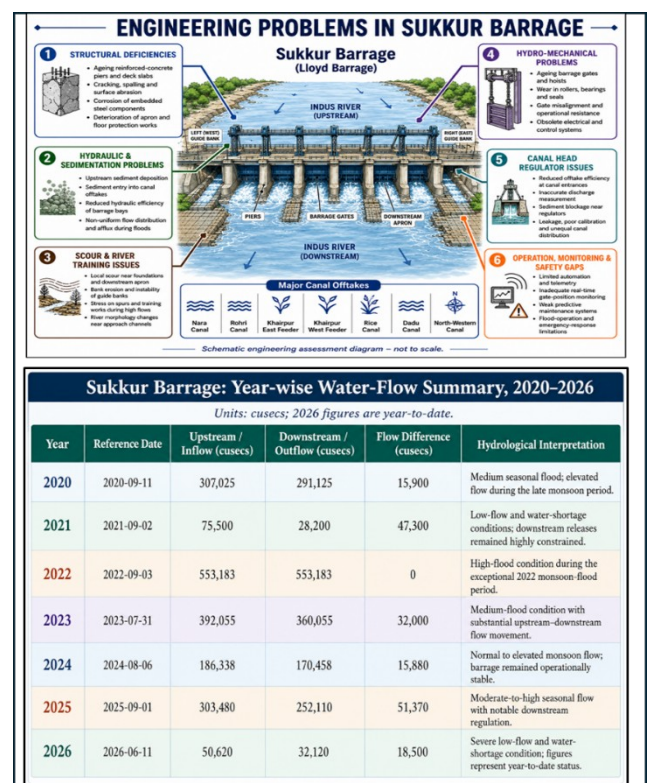


Fig. 13. Engineering problems of Sukkur Barrage

from deterioration, corrosion, seepage, and material wear due to aging. Reduced flow through the barrage lowers approach-channel performance, causes blockage of canal off-takes, and results in less even water distribution in the command area. Siltation is another problem that affects the barrage's hydraulic behavior. Downstream erosion due to local scouring, foundation stresses, and damage to river training structures also threaten the barrage during high floods. Aging gates and hoists, rollers, seals, embeds, and electrical systems not only reduce operational reliability but also delay irrigation and flood-flow regulation. The lack of a real-time telemetry system, automation of gates and hoists, accurate discharge measurement, and struc-

tural monitoring also limits decision-making. These engineering challenges warrant rehabilitation, sediment management, automation, and predictive maintenance.

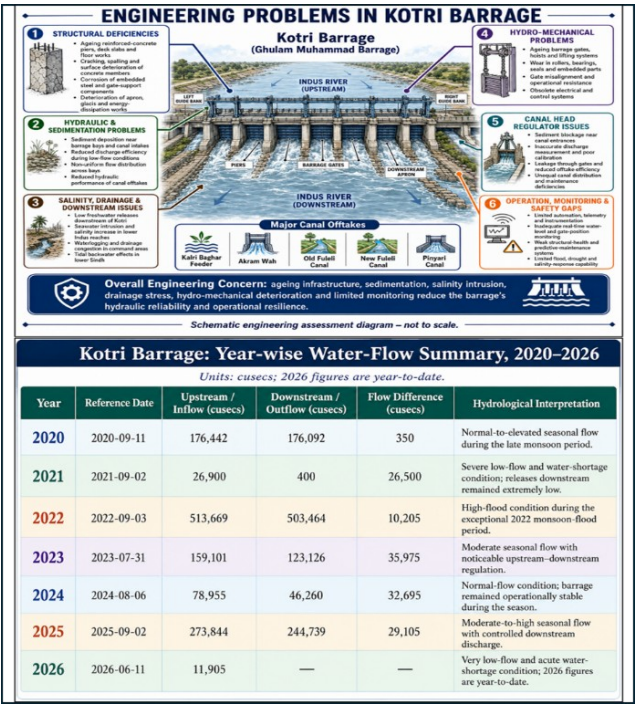


Fig. 14. Engineering problems of Kotri Barrage

Aging infrastructure, insufficient flow control, sedimentation, salinity intrusion, and coastal hydraulic stress are among the engineering challenges at Kotri Barrage. Corrosion, concrete deterioration, seepage, abrasion, and mechanical inefficiency can affect its gates, piers, aprons, hoisting systems, and canal head regulators. Its location in the lower Indus system makes it highly vulnerable to reduced downstream flows, tidal influence, seawater intrusion, and drainage congestion. Weak embankments, local scour, sediment deposition, and insufficient real-time monitoring further affect hydraulic performance. These evolving challenges affect Lower Sindh's operational dependability, irrigation effectiveness, flood-control capability, and climate resilience.

4.6 Discussion

The findings show that the combined effects of climate variability, uneven rainfall distribution, frequent floods, drought frequency, groundwater depletion, sedimentation, and aging water infrastructure are making Pakistan more hydrologically vulnerable. GIS-based spatial analysis shows that vulnerability is concentrated in arid and semi-arid regions of Balochistan, southern Punjab, Sindh, Tharparkar, Cholistan, and the lower Indus areas, while flood-prone districts along the Indus Basin remain highly exposed to extreme monsoon variability. The hydrological trend assessment also shows increasing stress on river flows, canal command regions, reservoirs, barrages, and groundwater-dependent zones. The engineering infrastructure review notes that reduced conveyance efficiency, seepage losses, poor telemetry, silt build-up, inadequate drainage systems, and insufficient real-time monitoring hamper effective water management. The results also demonstrate how

smart water-engineering solutions can greatly enhance water-use efficiency, early warning, infrastructure monitoring, and climate-adaptive decision-making. These solutions include GIS mapping, remote sensing, IoT-based sensors, SCADA systems, automated flow measurement, AI-supported flood forecasting, and digital water accounting.

Pakistan's water insecurity goes beyond a lack of water. It also involves managing hydrology, building structures that can withstand different climatic conditions, and using new technologies. Because of climate change, we are seeing less predictable rainfall, river outflows, and more frequent drought and flood events. Our current technology and practices are failing to cope with these challenges. Many regions suffer from drought stress and flood devastation, which further shows that we are not meeting the criteria for water resilience. Our country needs a more robust system to manage the complexities of climate-change-driven hydrological risk. As this paper shows, smart engineering can help fill some of those gaps. By collecting information in real time, we can forecast future outcomes, control operations, and make decisions based on facts. However, applying these methods will bring obstacles, such as properly managing these new technologies. More funding, education, and communication between provinces will be key. We need to implement these new technologies alongside traditional methods to meet SDG 6 and 13 by 2030. For example, monitoring groundwater tables and using efficient irrigation practices. We also need to repair existing infrastructure and build water resilience. As this paper shows, new technologies will not ensure water security without proper institutions.

Regarding sustainable water management, since 2001, responsibility for managing and regulating water resources in Pakistan has been decentralized to the provinces and municipal governments [35]. A primary issue in Pakistan's water management is the disparity in per capita water use between urban and rural areas. The Ministry of Water Resources issued the National Water Policy in April 2018 to address water resource management concerns in Pakistan. The National Water Policy of 2018 placed greater emphasis on the sustainable exploitation of water resources and introduced the notion of maximizing agricultural productivity per unit of water, sometimes referred to as 'growing more crop per drop' [36]. The 2024 floods caused an estimated PKR 3.2 trillion (US\$14.9 billion) in damage and affected 30 million people [37]. Pakistan experiences perpetual, unpredictable floods and droughts almost every year. Hence, it is imperative to recognize the importance of climate-resilient urban design, integrate climate change considerations into development initiatives, and formulate an appropriate governance strategy for the conservation, distribution, utilization, and preservation of precious water resources. Water scarcity and water quality issues have become major concerns in Pakistan in recent years.

Pakistan has suffered from unplanned urbanization,

which has negatively affected its water security. This has led to resource overexploitation, pollution, and unequal access to water. Urbanization has become a major problem in Pakistani cities like Karachi, Lahore, and Islamabad [38]. As a result, an inadequate water supply network, illegal groundwater pumping, and contamination of water resources have increased. Improper urban construction and encroachment on natural channels have reduced recharge and caused waterlogging in cities [39]. Which further reduced the quantity and quality of available water. Poor urban planning has also led to dumping waste from industries and households into water resources, contaminating them. This has reduced the amount of drinkable water [40]. Heavy groundwater use in urban areas has also lowered groundwater levels. All these problems have deteriorated Pakistan's water security and, if left unmanaged, will lead to serious consequences [41].

5. Conclusion

Flood occurrences and intensity are increasing. Climate change has increased the risk Pakistan faces from floods and droughts, altered rainfall patterns, groundwater depletion, and glacial melt. The study shows that Pakistan's water-security challenges stem from several factors, including weak governance, inefficient irrigation systems, insufficient storage capacity, weak drainage, limited real-time monitoring, and inadequate integration of engineering and technological solutions, in addition to physical scarcity. Vulnerability is unevenly distributed, according to spatial data from GIS-based rainfall and drought mapping. While flood-prone districts along the Indus Basin remain exposed to extreme monsoon variability, arid and semi-arid regions such as Sindh, Balochistan, southern Punjab, Tharparkar, Cholistan, and the lower Indus areas face severe drought and water-stress conditions. Infrastructure deterioration, sediment load, seepage losses, weak telemetry, and limited automation all reduce operating efficiency and climate resilience, according to engineering evaluations of barrages, canals, embankments, drainage systems, and water-control structures. In this regard, smart water engineering solutions offer a viable way to transform Pakistan's water management system. Technologies such as GIS, remote sensing, IoT-based sensors, SCADA systems, AI-supported flood and drought forecasting, digital water accounting, automated flow measurement, groundwater monitoring, and structural health assessment can enhance evidence-based planning, early warning, water-use efficiency, infrastructure safety, and equitable distribution. However, without institutional coordination, financial investment, experienced personnel, interprovincial cooperation, data transparency, and a long-term maintenance culture, technology cannot achieve water security alone. Therefore, an integrated national framework that incorporates climate-resilient infrastructure, smart technologies, hydrological data systems, inclusive governance, and sustainable resource management is necessary to achieve

UNSDG 6 and 13 by 2030. This strategy can support a secure, effective, and equitable water future, increase Pakistan's adaptation capacity, and reduce the risks associated with climate change.

6. References

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Table 1
Meteorological monitoring station datasets.

Serial	Zone/ Station	Latitude (E)	Longitude (N)	Elevation (meters)	Annual rainfall (mm)	
					Average	Trends/ Decade
Zone 1						
1	Astor	35°22′	74°54′	2167	481.19	−8.10
2	Balakot	34°23′	73°21′	980	1562.43	−38.37
3	Bunji	35°40′	74°38′	1372	153.12	7.71
4	Chilas	35°25′	74°6′	1250	186.25	6.11
5	Chitral	35°51′	71°50′	1499	474.42	−9.58
6	Dir	35°12′	71°51′	1369	1317.83	52.93
7	Garhi Dupatta	34°13′	73°37′	812	1551.92	−89.00
8	Gilgit	35°55′	74°20′	1459	134.52	6.86
9	Parachinar	33°52′	70°5′	1725	866.80	91.50
10	Sakardu	35°18′	75°41′	2209	223.29	10.00
11	Muzaffarabad	34°22′	73°29′	701	1519.17	−18.31
Zone 2						
12	Sialkot	32°30′	74°32′	251	975.25	19.76
13	Sargodha	32°3′	72°40′	187	446.17	28.00
14	Shorkot	30°47′	72°12′	150	278.10	19.00
15	Peshawar	34°1′	71°35′	359	459.40	39.60
16	Lahore	31°33′	74°20′	213	623.90	26.00
17	Kohat	33°34′	71°26′	510	571.20	10.00
18	Islamabad	33°37′	73°6′	507	1176.89	35.98
Zone 3						
19	Quetta	30°15′	66°53′	1600	244.00	−6.10
20	Zhob	31°21′	69°28′	1405	287.40	−5.39
21	Khuzdar	27°50′	66°38′	1231	235.17	14.89
Zone 4						
22	Rohri	27°42′	68°54′	66	99.10	7.75
23	Sibbi	29°33′	67°53′	133	163.15	12.60
24	Multan	30°12′	71°26′	122	200.80	9.00
25	Mianwali	32°33′	71°33′	210	525.87	52.67
26	Jacobabad	28°18′	68°28′	55	114.00	12.85
Zone 5						
27	Pasni	25°16′	63°29′	4	104.40	−3.85
28	Panjgur	26°58′	64°6′	980	103.50	−7.76
29	Nokhundi	28°49′	62°45′	682	40.8	0.14
30	Jiwani	25°4′	61°48′	56	105.60	−7.62
31	Hyderabad	25°23′	68°25′	40	176.00	−7.71
32	Dalbandin	28°53′	64°24′	848	85.60	−2.19
33	Karachi	24°54′	67°8′	21	202.40	−16.90

Table 2

ANOVA and SPSS results for monitoring stations datasets.

Description	Values	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Observation points		11	7	3	5	7
20 years average	valid/ missing values	296/4	178/6	119/5	176/7	120/1
Mean	Used values	69.53	65.80	35.78	24.45	33.15
	5% trimmed Mean	67.43	63.67	34.53	22.34	30.73
Median		61.13	59.05	31.40	20.10	26.00
Std. Error		3.71	3.70	1.28	1.05	3.30
95%CI	Lower Bound	62.28	60.42	29.10	21.47	28.25
	Upper Bound	72.80	68.40	34.48	23.63	37.60
Skewness		0.40	0.42	1.28	1.05	1.36
F-Value		1.85	0.89	3.65	1.33	5.79
Sig.		0.16	0.42	0.05	0.23	0.00

Table 3

Results of probability distribution analysis of four provinces, from mathematical modeling

District	Mean	SD	Coefficient of skew	Best fit K-S	Best fit A-D	Best fit RMSE	Highest distribution
Sindh							
Sukkur	49.0	38.5	1.929	GAM(0.044)	GUM(1.84)	LN2(7.90)	LN2(7)
Umerkot	102.9	68.9	1.044	GAM(0.030)	W2(0.60)	LP3(10.64)	GAM(7)
Tharparkar	135.9	76.9	0.499	GAM(0.045)	GUM(1.05)	LP3(10.97)	GAM(7)
Sukkur	47.9	38.5	1.980	GAM(0.044)	GUM(1.66)	LN2(7.11)	LN2(7)
Mirpurkhas	102.1	68.7	0.944	LN2(0.063)	LN2(1.94)	LP3(9.85)	LN2(4)
Karachi	89.8	71.4	1.562	AM(0.033)	GAM(1.47)	LN2(12.46)	GAM(4)
Jamshoro	76.0	60.5	1.304	GAM(0.032)	GAM(1.56)	LP3(11.86)	GAM(4)
Hyderabad	81.9	61.0	0.796	GAM(0.078)	GUM(1.75)	LP3(9.79)	GAM(6)
Badin	100.9	65.6	0.686	GAM(0.042)	W2(0.44)	LP3(8.72)	GAM(7)
Khairpur	75.9	58.9	1.465	GUM(0.014)	GUM(2.08)	LN2(7.55)	LN2(7)
Ghotki	45.9	34.4	1.698	LN2(0.013)	GUM(1.90)	LN2(5.21)	LN2(4)
Shikarpur	27.3	19.8	2.560	LN2(0.034)	GUM(1.63)	W2(6.16)	LN2(6)
Badin	100.9	65.9	0.685	GAM(0.040)	W2(0.42)	LP3(8.65)	GAM(7)
Balochistan							
Gwadar	29.2	13.5	1.468	N(0.035)	EXP(0.05)	LP3(2.36)	LP3(4)
Harnai	72.2	30.6	1.232	W2(0.089)	LN2(0.18)	LP3(5.29)	W2(5)
Chaman	68.9	25.9	0.805	LP3(0.015)	N(0.10)	LN2(2.95)	LP3(6)
Awaran	45.9	39.90	3.489	W2(0.320)	EXP(0.70)	LP3(13.98)	W2(5)
Chagai	25.9	12.95	1.80	LP3(0.019)	EXP(0.149)	LP3(3.00)	LP3(4)
Dukki	61.5	25.96	1.168	N(0.024)	GEV(0.22)	LN2(4.60)	LN2(8)
Jafarabad	31.8	22.98	3.265	W2(0.231)	EXP(0.40)	LP3(9.55)	W2(7)
Jhal Magsi	33.9	26.91	3.50	W2(0.273)	EXP(0.49)	LP3(10.43)	W2(6)
Barkhan	107.9	54.5	1.30	W2(0.120)	W2(0.06)	LN2(6.18)	LN2(6)
Kachhi	38.8	21.8	2.60	W2(0.130)	W2(0.8)	W2(6.40)	W2(3)
Punjab							
Lahore	429.4	126.9	0.533	W2(0.057)	LP3(0.24)	LN2(15.20)	LN2(7)
Sialkot	292.9	80.9	0.233	W2(0.053)	LP3(0.32)	LP3(11.11)	LP3(4)
Rawalpindi	312.9	80.4	0.306	GAM(0.022)	LP3(0.42)	LP3(12.25)	LP3(4)
Vehari	50.9	25.9	1.883	GAM(0.018)	EXP(0.12)	LN2(6.72)	GAM(5)
Multan	81.6	39.7	2.006	W2(0.122)	LN2(0.24)	W2(9.49)	LN2(6)
Sargodha	132.5	36.5	0.477	GAM(0.022)	LP3(0.32)	LN2(4.33)	GAM(7)
Sheikhupura	181.1	55.9	0.272	GAM(0.032)	LP3(0.18)	LP3(7.14)	GAM(5)
Rahim Yar Khan	50.9	32.3	2.110	W2(0.182)	EXP(0.44)	LN2(7.85)	LN2(6)
Okara	90.6	33.6	-0.231	GAM(0.054)	EXP(0.06)	GUM(4.15)	GAM(7)
Sahiwal	71.9	30.9	0.688	GAM(0.032)	EXP(0.13)	LP3(5.23)	GAM(6)
Narowal	308.0	106.0	-0.057	GAM(0.046)	LN2(0.12)	LP3(16.71)	GAM(6)
Muzaffargarh	50.5	25.1	1.258	W2(0.102)	W2(0.12)	LN2(4.37)	LN2(6)
Lodhran	48.6	26.6	1.724	W2(0.135)	EXP(0.32)	LN2(7.45)	LN2(7)
Khyber Pakhtunkhwa							
Peshawar	107.9	30.9	0.774	LP3(0.010)	LP3(0.33)	LN2(6.87)	LP3(4)
Swat	125.6	31.1	0.888	LP3(0.010)	GEV(0.55)	LP3(4.18)	GEV(6)
Tank	90.7	36.7	1.111	W2(0.073)	GAM(0.10)	LN2(5.62)	GAM(7)
Swabi	216.0	62.1	0.900	LP3(0.007)	GEV(0.34)	LN2(10.18)	LP3(7)
Nowshera	137.8	38.4	0.855	LP3(0.011)	LP3(0.33)	LP3(5.76)	LP3(3)
Mardan	180.3	55.0	0.917	W2(0.061)	GEV(0.31)	LP3(9.01)	GEV(6)
Mansehra	202.8	43.2	1.041	LP3(0.017)	GEV(0.66)	LP3(9.30)	GEV(6)
Haripur	250.9	69.8	0.655	W2(0.051)	LP3(0.34)	LN2(13.37)	LN2(5)
Shangla	179.3	42.5	1.300	W2(0.044)	GEV(0.55)	LP3(8.77)	GEV(7)
Orakzai	138.2	35.5	0.341	LP3(0.015)	LP3(0.41)	LP3(5.02)	LP3(3)