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Hydro-Climate Variability and Its Implications for Water Resource Sustainability in the Sahiwal Region of Pakistan

Sajjad Ahmad[1], Faakhar Raza[1], Sara Musaddiq[2], Mohammad Abdullah Saeed[3], Aqsa Nawaz[3], Shabnam Hameed[4], Sehrish Ramzan[3], Abdul Ghafoor[3], Amina Zara Chaudhary[3,5], Muhammad Azeem Akbar[3]

1. Pakistan Council of Research in Water Resources, Ministry of Water Resources, Islamabad, Pakistan
2. Department of Chemistry, The Women University, Multan 66000, Pakistan
3. Department of Chemistry, University of Sahiwal, Sahiwal, Pakistan
4. Department of Chemistry, Government Graduate College Sahiwal, Pakistan
5. Department of Chemistry, COMSATS University Islamabad, Lahore Campus

Abstract: Hydro-climatic variations pose significant risks to natural environment particularly water security and agri based activities in moderate-arid zones such as Sahiwal-Region, Pakistan. This main focus of this research study is to evaluate the impacts of climate change on rain fall patterns in Sahiwal region. For this task, ten years rainfall data (2014 –2023) was investigated and shifts in rainfall events over time were computed. Finally, this study outlines the critical implications for water resource management and propose climate-adaptive interventions. During the selected study period 92014-2023, the rainfall trends exhibited significant variations, ranging from 219 mm (2021, intense drought) to 625.62 mm (2015, extreme rainfall). Statistical analysis shows mean annual rainfall of 420.3 mm with a substantial fluctuation of 115.7 mm, indicating unpredictable shifts. The coefficient of variation approximately 29% further exhibits significant yearly variations. Regression modelling predicts a slight declined in raining for 2024 to 2028, though greater deviations remain. While expediting the rainfall patterns, it was observed that about 10% of years were considered as intense dry and 20% as intense wet, marking increased hydro-climatic risk. The tenure, 2017 to 2021 exhibited extended drought years while remaining years exhibited partial recovery. The shift in trends threaten groundwater recharge, prolonged water availability and crop productivity. This study analyzes raining trends from 2014- 2023 to assess their impacts on sustainability of water resource and climate resilience. The month wise data analysis for rainfall events indicates a divert toward monsoon intensity, characterized by an earlier onset in June, stronger raining pattern in July and reduced rainfall after monsoon. These variations in rainfall pattern create serious impacts on whole ecology. In adaptation response, the research evaluates the potential of rainwater harvesting (RWH) and managed aquifer recharge (MAR). Model calculations indicates that a standard 5000 ft^2 rooftop in Sahiwal urban area could yield approximately 118,600 liters annually, showing a high potential for decentralized water storage. The study suggests integrating RWH, recharge wells, enhanced irrigation approaches, and watershed-focused planning into climate adaption measures. The study recommends a rain water harvesting integrated with ground water recharged wells to reinforce the proactive and adaptive approaches to water management, planning into climate change adoption. These variations pose challenges for replenishment of groundwater, agriculture, and overall water resource management. This paper discusses adaptive measures, including harvesting of rainwater and groundwater recharge practices, to mitigate the climate-related water stress and preservation of precious fresh water to runoff through drains. The study points out the critical importance of sustainable water arrangements to reduce the destructive effects of hydro-climatic erraticism in moderate-arid zones of Punjab.

Keywords: Hydro-Climatic Variability, Resilience, Rain Water Harvesting, Sustainable water arrangements, Managed Groundwater Recharge

INTRODUCTION

Globally, climate change directly affects the water resources and agricultural systems. Freshwater availability is expected to be at higher risk due to the climate shifts, leading to variation in rainfall trends and water allocation. Fluctuation in the intensity, frequency, and seasonal difference of rain events have considerably affected supply of water for irrigation and crop production. The gap between water supply and demand has extended due to the agricultural operations and reduced river systems. Although agricultural water application is expected to increase by 19% by 2050 at the global level, many regions already have to face declining of water. Among the most drought-prone countries in the world, Pakistan has to face less than 240 mm of an average yearly rainfall. Pakistan includes into the class of “Severe Water Stress,” with per capita water availability calculated at around 1066 m^3. Developing countries including Pakistan often lack the framework to address the extreme wet and dry situations, enabling them particularly susceptible to the negative effects of climate shift [1].

Hydro-climatic variation is not only influenced by global climatic fluctuations, but have remarkable impacts on agriculture, water security, and economic activities, particularly in moderate-arid regions of Pakistan. Fluctuations in rainfall intensity and frequency lead to water shortage, reduced crop yields, and groundwater depletion. The country’s geographical diversity, including, extensive plains, coastal regions and mountainous areas make it highly susceptible to climate-related disturbances [2]. Hydro-climatic variation causes changes in rainfall, temperature, and other hydrological characteristics that affect the availability and distribution of water resources. This variability, driven by both natural climate and human-induced factors, plays a key role in determining agricultural productivity and water security [3].

Pakistan ranks among the countries most severely affected by extreme weather events in recent decades [4]. These climatic shifts have negatively influenced key sectors such as water, health, agriculture, and coastal ecosystems, thereby deepening poverty and susceptibility. Whereas national adaptation policies and frameworks have been initiated, their effectiveness largely depends on strong institutional coordination and inclusive implementation planning [5].

Regions with moderate aridity including Sahiwal experiences hydro-climatic variations at large scale due to the complex interactions between ocean–atmosphere, land-surface processes, and regional climatic conditions. Phenomena such as El Niño events, changes in Indian Ocean sea-surface temperatures, and atmospheric fluctuations significantly influence regional rainfall variability and drought frequency. The “dry gets drier, wet gets wetter” concept suggests that existing hydro-climatic conditions may intensify under ongoing climate change, with arid zones experiencing prolonged droughts and wetter regions facing increased flood risks Table 1 summarizes key impacts of climate fluctuations [3] Prolonged observations on raining between 2014 to 2023 in Sahiwal demonstrate variability in seasonal and annual rainfall trends. These variations affect the start and end of crop-production seasons, thus influencing water availability and agricultural productivity. Comparable trends have been documented in other moderate-arid zones i.e., Tanzania, where belated rainfall inhiation, reduced rainy seasons, and escalating drought occurrences aggravate water shortage and agricultural stress [6].

Climate predictions and observational data demonstrate increasing irregularity in precipitation, with prolonged dry spells and intensified raining. These changes directly effect on replenishment of groundwater and surface-water availability: both are important for sustaining agricultural livelihoods. Prolonged variability in rainfall patterns enhance water shortage and involve in socio-economic challenges, including migration, lowered food availability, and decline in income. Understanding hydro-climatic variability in such moderate-arid zones is therefore necessary for developing strategies for sustainable water resource management that enhance adaptive capacity and ensure long-term environmental and economic security [7]

Table 1: Impacts and threats of climate fluctuations

Impact Factor	Threats	References
Water Scarcity & Glacial Melting	Retreat of glaciers, erratic precipitation, prolonged droughts, and reduced river flows affecting agriculture and lives. Threatens food and water security, worsens during heatwaves and drought	[7]
Agriculture & Food Security	Fluctuating yields, disrupted crop cycles, pest/disease outbreaks, and soil degradation. Major threat to economy and livelihoods; adaptation in agricultural practices is vital.	[8]
Extreme Weather Events	Serious floods (2010, 2022), heatwaves, storms causing displacement, loss of life, property, and infrastructure. Increases poverty and migration risk; need resilient infrastructure & quick disaster response.	[9]
Coastal & Urban Vulnerability	Sea-level rise, cyclones, sea water intrusion in Indus Delta, urban flooding, heat islands. Damages to fisheries, mangroves, and urban economy; requires coastal protection and urban planning.	[10]
Health & Migration	Heat stress, vector diseases, maternal and child health risks, migration due to climate shocks. Health sector under strain; migration affects social structure; special focus on vulnerable populations.	[11]
Adaptation & Mitigation	National Climate Policy, National Adaptation Plan, reforestation, climate-resilient agriculture, rainwater harvesting. Good policy progress, but implementation, funding, and local engagement need improvement.	[12]

In view of the hydro climatic risks, adoption of adaptive water management and agricultural approaches is necessary. Among the main measures which may be implemented in this regard is the collection and storage of rainwater during intense rainfall that stabilize water supplies during dry spell. Studies show its effectiveness in moderate-arid zones to support irrigation and reduction of groundwater depletion [13]. Likewise, replenishment of groundwater by managed aquifer recharge techniques, involving providing water on agricultural land or employing recharge wells, increase groundwater storage, thus improving the adaptive capacity of dry spell and water sustainability [14].

The Sahiwal zone, largely dependent on agriculture, is susceptible to rainfall shift. Integrating conventional knowledge with modern technological solutions can increase adaptive capacity in susceptible zones, supporting sustainable water and food management under climate change. Current study analyzes a ten years records of rainfall data (2014–2023) to identify trends and variability in rainfall, evaluate implications for water resource sustainability and to recommend adaptive measures i.e., collection and storage of rainwater harvesting and replenishment of groundwater.

METHODOLOGY

The main objective of this study is to evaluate hydro-climatic variability in the Sahiwal region Pakistan, concentrating on rainfall trends recorded between 2014 and 2023 and their impacts on management of sustainable water resource, agricultural yield and groundwater replenishment. From computed data, a model calculation model is quoted in research incentivization. Furthermore, it seeks to identify and recommend adaptive strategies that can enhance climate resilience and secure water availability for the region's population and economy.

Study Area

When defining boundaries of the Sahiwal Region for climate-based studies, the goal is to identify an area with relatively homogeneous climate characteristics (rainfall, temperature, humidity, and soil-water interactions). Based on climate data, physiography and Agro-Ecological conditions in Punjab, Pakistan, the following considerations can guide the boundaries: Sahiwal is located in the central Punjab province of Pakistan. It has a semi-arid climate, with rainfall largely concentrated in the monsoon season. Agriculture is the primary economic activity, and groundwater is an important source for irrigation and domestic use. Sahiwal district lies roughly between 30.5°–31.5°N latitude and 72.5°–73.5°E longitude. It is part of the central Punjab plain, bordered by Okara (east), Pakpattan (south), Faisalabad (northwest), and Vehari (southwest). For climate homogeneity, slight adjustments are recommended,

Climate Homogeneity Criteria

Rainfall: Annual precipitation ranges from ~200 mm (dry years) to ~625 mm (wet years), mostly during monsoon (July–September).

Table 2: Climate Homogeneity Criteria – Summary Table

Parameter	Characteristics	Criteria for Homogeneity
Rainfall	Annual precipitation: 200–625 mm; mostly during monsoon (July–September)	Areas with rainfall within ±10–15% of mean annual rainfall (~417 mm)
Temperature	Warm semi-arid climate; mean 24–26°C; extremes 5°C (winter) to 45°C (summer)	Zones with consistent seasonal temperature patterns and similar annual range
Evapotranspiration	High potential evapotranspiration in summer due to heat and low humidity	Areas with comparable PET and seasonal variability

Soil-Water Interaction	Predominantly alluvial soils with moderate infiltration; groundwater depth 5–15 m	Regions with similar soil permeability and groundwater recharge characteristics

Climate-homogeneous zones in Sahiwal are defined as areas where rainfall, temperature, evapotranspiration, and soil-water interactions show consistent patterns. These zones are suitable for targeted water management interventions such as rainwater harvesting and groundwater recharge, ensuring effective climate resilience planning.

Proposed Climate-Homogeneous Boundaries

Table 3: Proposed Climate-Homogeneous Boundaries

Boundary	Coordinates / Features	Justification
Northern Boundary	Approx. 31.5°N (toward Faisalabad District)	Characters shift from semi-arid zone of central Punjab to relatively wetter central plains
Southern Boundary	Approx. 30.5°N (toward Pakpattan & Vehari)	Avoids arid southern fringe and retains similar rainfall pattern
Eastern Boundary	Approx. 73.5°E (toward Okara)	Consistent rainfall and soil type; avoids more flood-prone areas along Ravi Canal
Western Boundary	Approx. 72.5°E (toward Vehari)	Keeps area within uniform irrigation and groundwater regime

Sahiwal District core (30.5°–31.5°N, 72.5°–73.5°E) as the primary climate-homogeneous boundary with Area Coverage: ~4,500–5,000 km². Northern Sahiwal (Faisalabad border): Slightly higher rainfall, intensive irrigated agriculture. Central Sahiwal (Sahiwal-Chichawatni): Semi-arid, moderate rainfall, mixed rainfed-irrigated agriculture. Southern Sahiwal (Pakpattan-Vehari border): Lower rainfall, risk of drought, higher evapotranspiration. This zoning allows targeted interventions like rainwater harvesting and groundwater recharge in the most vulnerable areas. Use Sahiwal District core (30.5°–31.5°N, 72.5°–73.5°E) as the primary climate-homogeneous boundary. The potential of rainwater harvesting is inherently linked to rainfall quantity and distribution. The region receives an average annual rainfall sufficient to support RWH initiatives. While monthly variability exists, peak precipitation during the monsoon months offers optimal collection opportunities. (Specific rainfall data such as average monthly and annual figures 1 and 2 are assumed to be included in the presentation's graphs, and would further support detailed system design.).

Data Collection and Computation

Annual rainfall data for 2014–2023 were obtained from regional meteorological records. The key parameters analyzed include:

- Annual rainfall (mm)
- Deviation from long-term average
- Month wise change in rain fall patterns in various years

- Year-to-year variability.
- A model computation for rain water harvesting (RWH).

The data is tabulated in table 2 and converted into meaningful indicator values by applying statistic tools.

Table 4: Statistical analysis of rainfall data and inferences

Year	Rainfall (mm)	Mean (mm)	Deviation (X- µ) (mm)	$(Xi\text{-}\mu)^2$	Z-score (σ) std. Devs. from mean
2014	488.34	420.3	68.04	4630	0.59
2015	625.62	420.3	205.32	42156	1.77
2016	405.45	420.3	-14.85	221	-0.13
2017	291.4	420.3	-128.9	16626	-1.11
2018	341	420.3	-79.3	6288	-0.69
2019	516	420.3	95.7	9159	0.83
2020	370	420.3	-50.3	2530	-0.43
2021	219	420.3	-201.3	40523	-1.74
2022	528.88	420.3	108.58	11799	0.94
2023	417.34	420.3	-2.96	9	-0.03

The rainfall data for past ten years (2014-2023) was interpreted by using the various statical tools and graphical presentations. The year wise data graphical presented in figure.4 and also drawing the various indicators like annual variations in rain fall, average rain fall and rain fall trend in last 10 years.

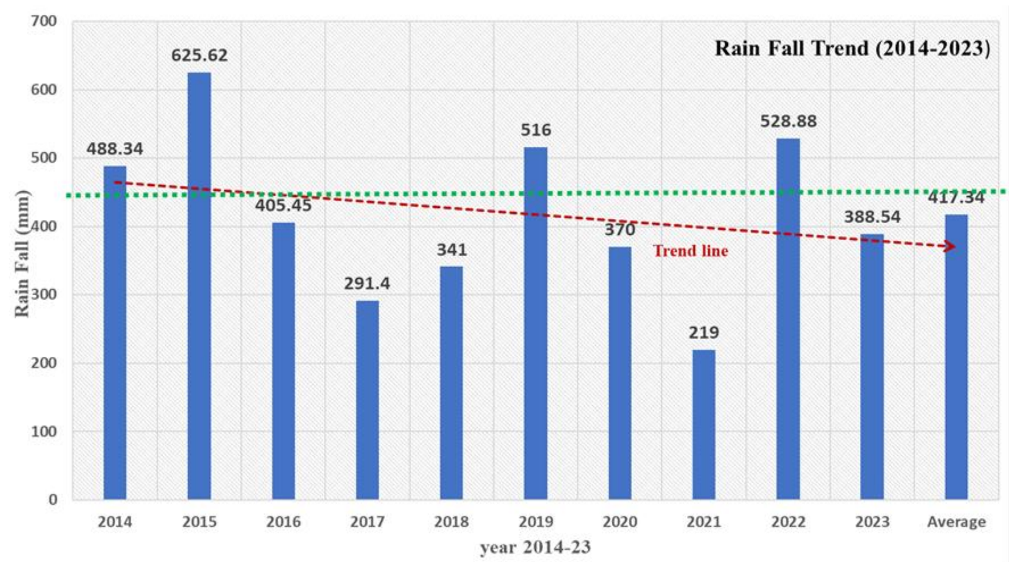

Figure 1: Average Annual Rainfall - Sahiwal Region

The plotted graph is interpreted for various technical indicators and information's which are summarized in the **table. 5**.

Table 5: Summary for various technical indicators for rain fall data (2014-2023)

Graph Indicator	**Summary**
Overall Trend	Slight declining trend in rainfall over the decade.
Highest Rainfall Years	2015 (625.62 mm), 2022 (528.88 mm) – unusually wet years.
Lowest Rainfall Years	2021 (219 mm) – critically low; also 2017 (291.4 mm), 2020 (data partly visible).
Rainfall Variability	High fluctuation between years; no stable pattern.
Mid-Decade Decline	Sharp drop from 2015 to 2017 (625 mm → 291 mm).
Short-Term Recovery	Partial increases in 2019 and 2022, but inconsistent.
Average Rainfall (10 years)	417.34 mm (several recent years fall below this).
Key Implication	Increasing irregularity, emerging drought risk, reduced water reliability.

To give the real yearly rainfall data for visual comparison, a graph is ploted between the rainfall (y-axis) and series of years (x-axis) which is used for multiple analytical and visual indicators to interpret rainfall behavior, trends, and future predictions. Each element provides a specific scientific meaning:

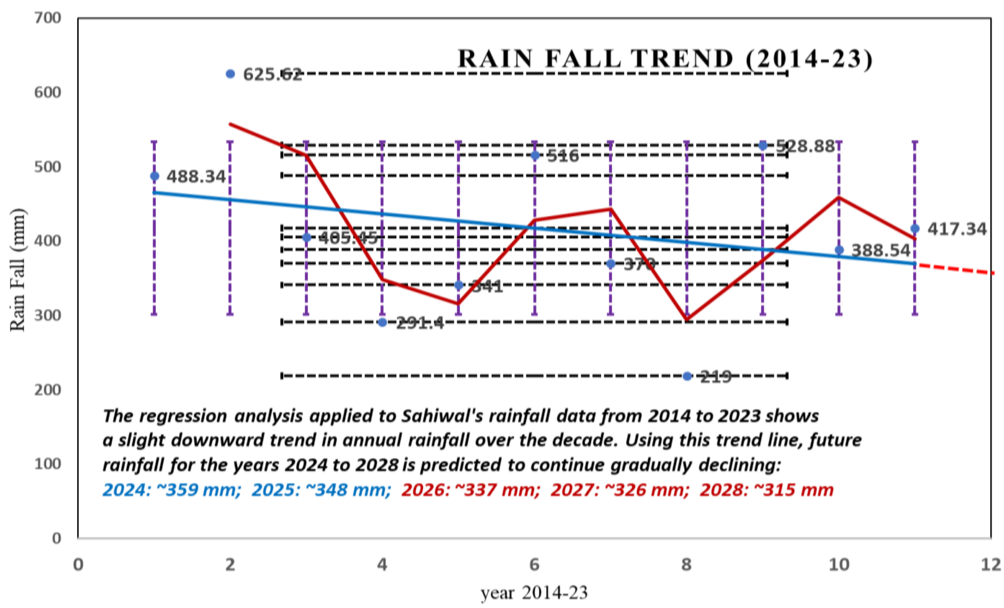

Figure 2: Observed Rainfall Trend (2014-2023) and Predicted Regression Line (2024-2028)

The regression trend line, and predicted rainfall for the next five years. The predictions suggest increasing risk of water scarcity if the trend persists, underscoring the importance of adaptive water management.

The regression analysis applied to Sahiwal's rainfall data from 2014 to 2023 shows a slight downward trend in annual rainfall over the decade. Based on this trend line, future rainfall for the years 2024-2028 is progressively decreasing.

Table 6: Predicted rainfall patterns for the future

Year	Predicted Rainfall (mm)	Standard Deviation Interpretation
2024	359	By using standard deviation (±115.7 mm) of average, predict the possible rain fall but still focus to substantial changes reliant on historical data.
2025	348	Approaching the lower range; actual values could deviate widely high standard deviation means planning must account for extremes.
2026	337	Slight downward trend continues; rainfall could easily be much more or less than prediction due to historical variability.
2027	326	Below average; risk of dry year is substantial given past deviations far from the mean.
2028	315	Trend indicates continued decrease, but high standard deviation means both drought and wetter years are still possible.

With a standard deviation of 115.7 mm over the last decade, rainfall in Sahiwal is highly variable. Although the regression predicts gradual decline, year-to-year rainfall may fluctuate widely above or below these predictions, emphasizing the need for adaptive water management strategies that can handle both drought and flood scenarios. The possible risk modelling is summarized as below;

Table 7: Risk modelling calculation for Sahiwal rainfall data (2014-2023)

Statistical modelling	Calculation / result/interpretation
Mean rainfall (mm)	420.3
Standard deviation (mm)	115.72
Extreme dry threshold	304.58 (mean - std. dev.)
Extreme wet threshold	536.03 (mean + std. dev.)
Dry years	2 (rainfall ≤ 304.58 mm)
Wet years	1 (rainfall ≥ 536.03 mm)
Normal years	7 (between dry and wet threshold)
Probability dry	20%
Probability wet	10%
Probability normal	70%
Vulnerability summary	Moderate risk in most years. Flood risk is low to moderate.
Exposure	High exposure: Majority of area relies on rainfall for crops and groundwater recharge.

Risk summary	Moderate risk overall; but severe dry or wet years (drought or flood) are possible due to high variability.

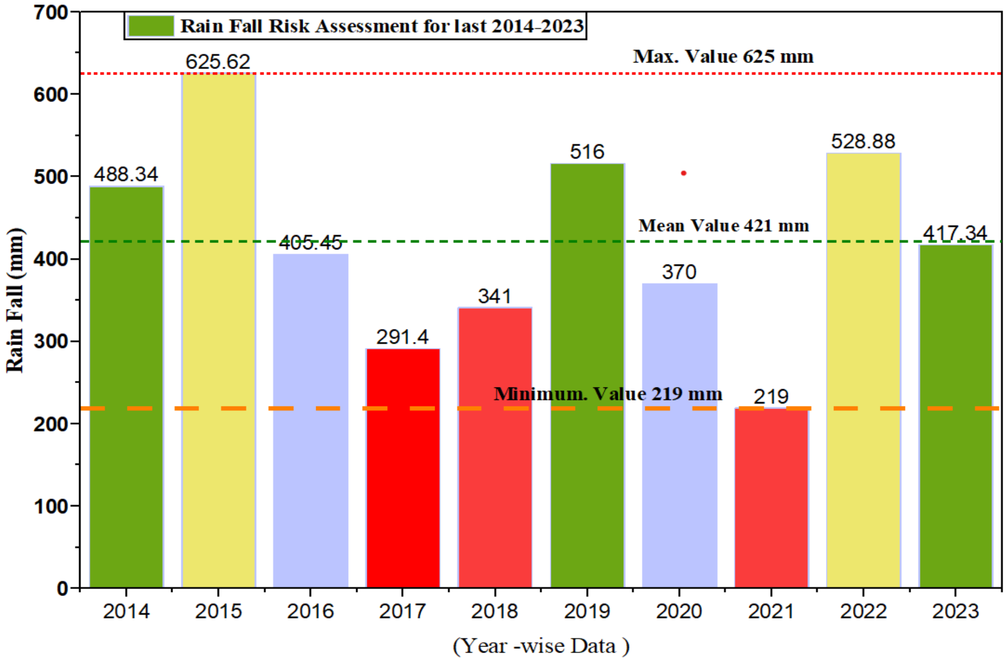

Figure 3: Rainfall Statistical Analysis and Risk Assessment for Sahiwal Region (2014-2023)

The study used statistical analysis to quantify rainfall variability:

- Mean and standard deviation of annual rainfall
- Coefficient of variation (CV) to measure relative variability
- Comparison of annual rainfall against the decadal average (417.34 mm)
- Identification of extreme wet and dry years

Rainfall Patterns (2014-2023)

Table 8: Year to year rainfall variations

Year	Rainfall (mm)	Deviation from Average (mm)	Remarks
2014	488.34	+70.99	Above average
2015	625.62	+208.28	Peak rainfall year
2016	405.45	-11.89	Near average
2017	291.40	-125.94	Significant drop
2018	341.00	-76.34	Below average
2019	516.00	+98.66	Above average
2020	370.00	-47.34	Slightly below average
2021	219.00	-198.34	Lowest rainfall year

2022	528.88	+111.54	Strong recovery
2023	388.34	-29.00	Slightly below average
Average	417.34	—	Reference

- Highest rainfall: 2015 (625.62 mm)
- Lowest rainfall: 2021 (219 mm)
- Coefficient of variation (CV): ~29% → indicates high variabilit
- Rainfall exhibits large inter-annual fluctuations, with wet and dry extremes.
- The period 2017-2021 shows a persistent dry trend, while 2022–2023 shows partial recovery.
- No consistent linear trend is observed, highlighting unpredictable rainfall patterns.
- The graphical visuals the rainfall (2014–2023) risk zones are color-coded and remarked as:
  - Red: Dry years (below extreme dry threshold)
  - Green: Normal years
  - Yellow: Wet years (above extreme wet threshold)
  - Threshold lines for mean, extreme dry, and extreme wet for context

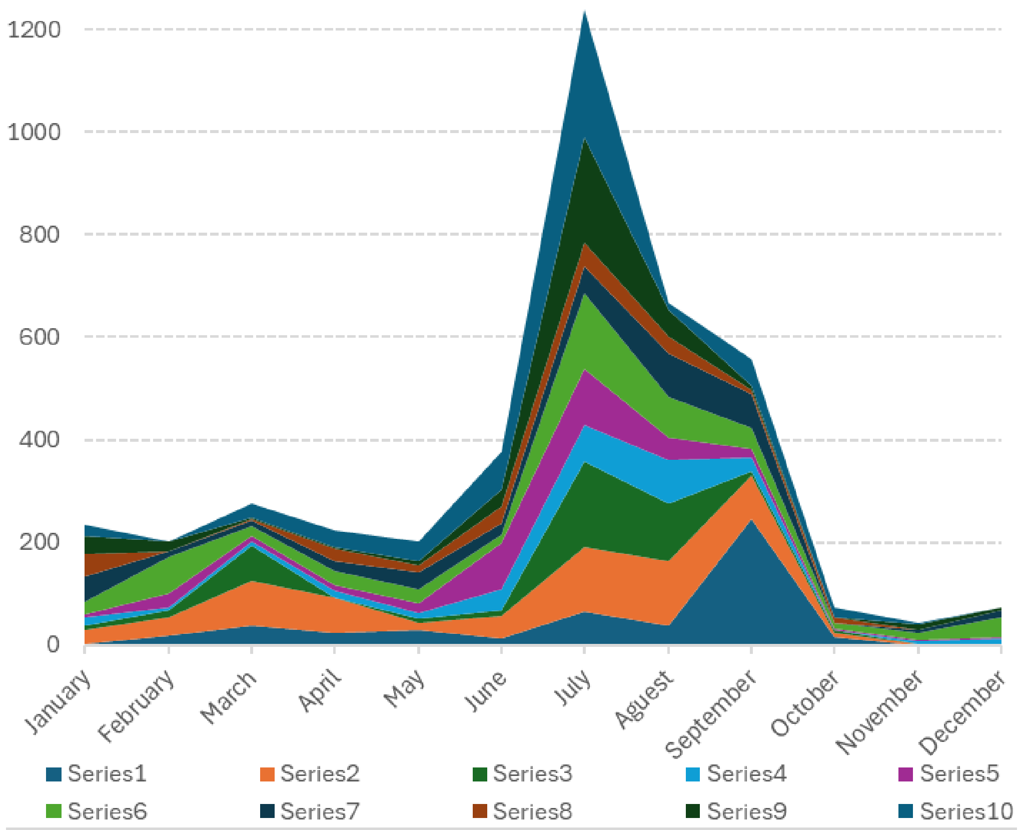

Figure 4: Month wise Rain Fall patterns for years 2014 -2023

Table 9: Monthly rainfall assessment

Year	Series	Interpretation of Rainfall Pattern (Month-Wise)
2014	Series-1	Low rainfall Jan–May; moderate increase in June; sharp monsoon peak in July; strong rainfall in August; decline in September; very low Oct–Dec.
2015	Series-2	Slightly higher early-year rainfall than 2014; noticeable pre-monsoon rise in March; good monsoon peak in July; steady decline August–September; dry end of year.
2016	Series-3	Stronger spring rainfall (Feb–March); moderate May rainfall; high July monsoon, slightly stronger than Series 1 & 2; good August levels; reduced from September onwards.
2017	Series-4	Low Jan–May; small rise in March; major spike in July similar to Series-3; moderate August; fast decline in September; dry October–December.
2018	Series-5	Higher March rainfall; slightly wetter spring; strong rise in June; high July rainfall but lower than peak years; August still good; then steep fall.
2019	Series-6	One of the stronger pre-monsoon years; higher April rainfall; very strong June rise; solid July monsoon; good August; notable September presence.
2020	Series-7	Wettest year overall; sharp June surge; extremely high July monsoon peak (highest among all years); August also very strong; gradual decline thereafter.
2021	Series-8	Moderate early months; visible rise from May; strong monsoon but weaker than 2020; July–August still major peaks; declining afterward.
2022	Series-9	Higher than average monsoon; strong March rainfall; pronounced June jump; strong July peak comparable to 2019; moderate August; September decline.
2023	Series-10	Lowest variability; overall low rainfall except July; modest monsoon, lower than most years; November–December slightly higher compared to 2014–2022.

Rainfall Pattern Change Report (2014-2023)

Over the past decade, rainfall patterns show a clear shift marked by increasing monsoon concentration and declining spring and autumn rainfall. Early year months (January–May) have remained consistently dry, with only minor fluctuations. The monsoon now arrives earlier in June, followed by an intensified peak in July, especially visible in 2019–2020. Post-monsoon rainfall in September has progressively declined, leading to a shorter effective rainy season. The intensity of severe rainfall events has risen, showing greater variations and unpredictability. Years such as 2020 indicate unusually elevated peaks, exhibiting monsoon volatility. Climate projections propose future rainfall is likely to become more episodic, characterized by shorter yet more severe bursts. Overall, the pattern indicates a shift toward climate-change-driven monsoon compression, increasing the risk of floods, droughts, and agricultural stress.

INTERVENTION MEASURES TO HYDRO-CLIMATIC CHANGE

In future plannings, climate change is a very important factor owing to ultimate impacts as unusual changes in rainfall patterns, seasons and droughts. All these are linked with economical security of our water resources. So, this change i may be realigned by adopting new water conservation strategies and management. Pakistan holds most of its land as arid or semi- arid zones, the rainfall data for semi-arid zones ranges from 350mm to 510mm per year. There is dire need to adopt the water conservation strategies to save precious water resources. Rainwater is an imperative source of fresh water and has a significant potential of storage and recharging the groundwater aquifer. The most practicable and common intervention is rain water harvesting and ground water recharge. The main objects are suggested are summarized as under.

- Implement climate-resilient rainwater harvesting (RWH) and Managed Aquifer Recharge (MAR) systems to enhance groundwater storage.
- Mitigate climate-induced water scarcity in urban and rural region of Sahiwal.
- Build community capacity and awareness on water conservation and adaptation.

MODEL CALCULATION: RAINWATER HARVESTING POTENTIAL IN SAHIWAL REGION

To assess the viability of RWH in the region, a model calculation was conducted for a typical building with a 5000 ft^2 (465 m^2) rooftop area (18 Marla) PCRWR –Office Sahiwal.

$$Q = C \times I \times A / 1000$$

Where:

Q = Runoff volume in cubic meters (m^3)

C = Runoff coefficient (0.8–0.9 for brick masonry roofs)

I = Rainfall (mm)

A = Rooftop area in square meters (m^2)

Table 10: Average precipitation levels

Scenario	Rainfall (mm)	Rooftop Area (m^2)	Runoff Coefficient	Potential Runoff (m^3)	Potential (Litters)
Monthly Average Rainfall	35	465	0.9	14.6	14,600
Maximum Monthly Rainfall Monsoon period)	123	465	0.9	51.5	51,500
Annual Average Rainfall	417	465	0.9	174.5	174,500

This implies that a single 5000 ft^2 rooftop could potentially harvest around 118,600 litters of rainwater annually under the given assumptions. In average approximately 34500 liters /1000 ft^2 roof top area rainwater could harvested annually.

Figure 5: Installed Rain Water Harvesting System in WQL PCRWR-Sahiwal

RESULTS AND DISCUSSION

Annual Rainfall Variability (2014–2023)

The decade-long rainfall record for the Sahiwal region indicates high inter-annual variability, with rainfall ranging from a maximum of 625.62 mm in 2015 to a minimum of 219 mm in 2021. The average annual rainfall over the period was 420.3 mm, with a notable variability f 115.7 mm, producing in a coefficient of variation of approximately 29%. This shows significant variations in rainfall, characteristic of semi-arid climates.

The observed rainfall pattern summarized as:

- Three significant wet years: 2015, 2019, 2022
- Two extreme dry years: 2017 and 2021
- Multiple near-average but fluctuating years

The risk modelling shows that 20% of the years are extreme dry, 10% extreme wet, and 70% moderate/normal. Such variation enhances exposure to both droughts and short-tenure severe rain events, placing stress on agricultural communities dependent on groundwater. The five-year droughts from 2017 to 2021 are particularly concerning, showing extended pressure on groundwater resources.

Trend Analysis and Future Rainfall Projections (2024–2028)

A linear regression analysis of annual rainfall exhibits a slight yet consistent declined, proposing further decrease in rainfall if existing climatic conditions remain unchanged. The forecasted rainfall for 2024 to 2028 is between 315 mm and 359 mm, all below the historical average.

However, because of the high standard deviation, actual rainfall could differ substantially from the predictions, showing that both drought and above-average rainfall may still occur. This uncertainty highlights the need for adaptive planning that may support water availability during droughts and reducing flood impacts under extreme wet conditions.

Month-wise Rainfall Shifts and Monsoon Concentration

Comparative analysis of monthly rainfall patterns from 2014 to 2023 shows a notable change in the seasonal pattern: The key notable shifts are summarized as follows:

- Earlier Monsoon Arrival: Rainfall onset has shifted from early July towards late June, indicating a faster buildup to the monsoon cycle.
- Increased Monsoon Intensity: The July rainfall peak has become more noticeable, especially during 2019 to 2020, when unusually severe monsoon bursts contributed for a considerable portion of the yearly rainfall
- Decline in Pre- and Post-Monsoon Rainfall: Rainfall from January to May remains at low level, whereas September–October rainfall has declined over time, that results in a shorter full rainy season.
- Rise of Episodic Heavy Events: Short, high-intensity events, especially in 2020, shows the impact of climate-change-derived monsoon depletion, with fewer rainy days but increased rainfall intensity per event.

These monthly shifts directly affect water availability, cropping schedules, and groundwater replenishment.

Implications for Water Resource Sustainability

Groundwater in Sahiwal is a chief source for irrigation and household water supply. However, the transition to intense yet short duration rainfall decreases infiltration, leading to reduced ground water recharge. The prolonged dry spell from 2017 to 2021 probably led to accelerated groundwater depletion, promoting farmers to extract water from greater depths. Agriculture is highly dependent on monsoon rainfall. The following key risks were highlighted:

- Delayed or weak rainfall onset disrupts sowing times of major crops such as cotton, maize, and fodder.
- Excessive July rainfall can cause waterlogging and crop failure.
- A shortened monsoon tenure enhances reliance on tube-well irrigation.
- In dry years, reduced soil moisture recharge adversely affects winter crop production.

Monsoon variability poses serious challenges to traditional farming systems, emphasizing the need for climate-smart agriculture.

Rainwater Harvesting (RWH) Feasibility and Potential

A model estimation for a 5000 ft^2 (465 m^2) rooftop with a runoff coefficient of 0.9 shows:

- The average monthly rainfall is 14,600 L
- 51,500 L during peak monsoon months
- ~118,600 L annually available for rooftop harvesting

These values strongly support the feasibility of decentralized RWH systems in semi-arid areas like Sahiwal, particularly for:

- Household-level storage
- Institutional buildings
- Schools and offices
- Supplemental irrigation
- Managed aquifer recharge (MAR)

With appropriate filtration and storage infrastructure, RWH can significantly reduce pressure on groundwater.

Integration of Climate-Resilient Interventions

Climate Change Interpretation

- Increased rainfall variability and occurrence of extreme events align with broader regional climate change projections.
- The high CV indicates a growing unpredictability, suggesting that reliance on traditional water management practices may be insufficient.

Adaptive Measures

To mitigate these impacts, the study recommends:

- Rainwater Harvesting: Collect and store monsoon rainfall to support irrigation and replenish groundwater reserves.
- Groundwater Recharge Practices: Construction of recharge wells and check dams to enhance aquifer replenishment.
- Integrated Water Management: Adoption of watershed-based planning and water-saving irrigation techniques.
- Expansion to Punjab Province: Scaling the interventions to other vulnerable districts for regional resilience.

CONCLUSION

In the Sahiwal region, extreme dry and wet years pose major challenges to the sustainability of water resources, leading to a high degree of hydroclimatic variations. Statistical analysis of rainfall data between 2014 and 2023 exhibits considerable unpredictability, emphasizing the need for quick adaption steps. Implementing sustainable practices, including rainwater harvesting and groundwater recharge can improve resilience and ensure water security for both agriculture and local communities.

RECOMMENDATIONS

1. Establish regional water management strategies that incorporate rainwater harvesting techniques.
2. Encourage community-based initiatives for groundwater recharge.
3. Promote climate-resilient agricultural measures to manage rainfall variability.
4. For strategic planning, conduct comprehensive research on long-term hydro-climatic patterns throughout Punjab.

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