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Warming summers and increasingly erratic seasonal rainfall, 2015-2025: evidence of climate variability, drought years and implications for agriculture and water security in Tarnab Peshawar

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Article

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Posted Date: November 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11532675/v1

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Additional Declarations:
No competing interests reported.

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Warming summers and increasingly erratic seasonal rainfall, 2015-2025: evidence of climate variability, drought years and implications for agriculture and water security in Tarnab Peshawar

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Highlights

- Summer warmed less faster (-0.05 °C/yr) than winter (0.09 °C/yr) over 2015–2025
- Annual rainfall ranged from 300 to 823 mm with strong inter-annual swings
- Spring rainfall was the most erratic season (CV 64%); summer the most reliable (45%)
- Three of eleven years fell below 75% of mean annual rainfall

Abstract

Understanding recent changes in temperature and rainfall is essential for planning agriculture and water resources in climate-sensitive regions. We analyzed eleven years (2015–2025) of daily temperature and rainfall records from Agriculture Research Institute Tarnab-Peshawar, Pakistan to describe seasonal temperature patterns, annual and seasonal rainfall distribution, rainfall reliability and meteorological drought. Mean summer temperature declined by -0.54 °C (-.05 °C yr^{-1}), mean winter temperature rose by 0.91 °C (0.09 °C yr^{-1}) and mean annual temperature by 0.57 °C (0.06 °C yr^{-1}) between 2015 and 2025, indicating that summer is warming less as compared to winter and the annual mean. Annual rainfall averaged 510.7 mm and ranged from 300.3 mm (2023) to 822.8 mm (2015). Rainfall was bimodal, with spring (mean 155.1 mm) and summer (204.2 mm) as the main wet windows; spring was the most erratic season (coefficient of variation, CV, 64%) and summer the least (45%). Using a threshold of 75% of mean annual rainfall, 2016, 2023 and 2025 were classed as drought years, and 2021 was marginal. Wet years were followed by dry years (2024 → 2025), and the pattern of rainfall concentrated in single seasons raises the risk of both flash flooding and drought. Trend analysis using the Hamed–Rao modified Mann–Kendall test revealed statistically significant decreasing trends in annual rainfall (Sen's slope = −19.69 mm $year^{-1}$, p = 0.032) and summer rainfall (Sen's slope = −9.93 mm $year^{-1}$, p = 0.001). In contrast, annual mean temperature (Sen's slope = −0.0663 °C $year^{-1}$, p = 0.2758) and summer temperature (Sen's slope = −0.1057 °C $year^{-1}$, p = 0.2758) exhibited decreasing but statistically non-significant

trends. These findings highlight the need for heat-tolerant crop management, rainwater harvesting and drought-adapted planning in the region.

Keywords: climate variability; summer warming; rainfall variability; meteorological drought; coefficient of variation; water security; Tarnab-Peshawar

1. Introduction

Global mean surface temperature has risen by about 1.1 °C above the 1850–1900 baseline, and the frequency and intensity of hot extremes and heavy precipitation events have increased in most regions (Intergovernmental Panel on Climate Change [IPCC], 2021). South Asia is particularly exposed: observations show rising temperature extremes and changing rainfall extremes across the region (Sheikh et al., 2015).

For agriculture, the seasonal distribution of rainfall and the occurrence of drought matter as much as annual totals. Droughts are commonly characterized using rainfall-based indices that compare observed precipitation with a long-period average or normalize it over different time scales (McKee et al., 1993; Svoboda and Fuchs, 2018), and temperature-sensitive indices have been proposed to capture the effect of warming on drought (Vicente-Serrano et al., 2010).

Climate variability and drought with substantial spatial and temporal variability in temperature and precipitation is a popular research topic in Pakistan and Khyber Pakhtunkhwa (KP). At the national scale, increasing temperature and significant precipitation trends have been reported across different agro-climatic regions of Pakistan. While semi-arid regions have been identified as particularly vulnerable to drought (Adnan et al., 2017). In KP, an analysis of 15 meteorological stations for the period 1971–2015 identified considerable spatial and temporal variability in rainfall and two prominent dry periods during 1984–1989 and 1998–2002 (Rahman et al., 2018). A subsequent assessment identified major drought periods during 1971–1974, 1984–1989, 1998–2004 and 2017–2018 with reports of ample spatial differences in rainfall and drought trends across KP (Rahman et al., 2021). For Peshawar, analysis of 30 years of observatory data (1981–2010) reported increasing trends in minimum and mean temperature and relative humidity, while rainfall showed a decreasing trend and maximum temperature showed no significant change (Shah et al., 2012).

Despite some studies an important local-scale knowledge gap remains. Previous research in KP has largely focused on provincial-scale spatial variability, long-term rainfall and drought indices, or individual climate variables, while the Peshawar-specific study by Shah et al. (2012) focused primarily on long-term trends in annual temperature, rainfall and relative humidity

(Rahman et al., 2018; Rahman et al., 2021; Shah et al., 2012). Comparatively less attention has been given to an integrated assessment of multiple agro-meteorological variables and their variability in relation to local agricultural conditions. But some recent local studies performed at Tarnab: such as (Khan and Shafi, 2024); (Shafi and Khan, 2025) are encouraging researchers to cope with this gap. The present study addresses this gap by examining climate variability at the local observatory scale and interpreting the observed variations in the context of agricultural conditions. Such site-specific analysis is important because spatially averaged or province-wide assessments may not fully represent local and seasonal variations that are relevant to agricultural planning and crop management.

The study area is located at the rural outskirts of Peshawar. Peshawar Basin is an agriculturally intensive and water-dependent region with the Kabul and Swat Rivers as its major surface-water sources, and approximately 60% of it is classified as cropland (Khan et al., 2021) with wheat, maize and sugarcane occupying the largest shares of cropland. Tarnab has long been acknowledged as the province's center for water research and agricultural development. High-yielding, disease-resistant, and climate-resilient crop types were introduced by Tarnab (Ullah et al., 2026). Deep aquifers and surface water from the Kabul and Swat rivers are crucial to Peshawar's agricultural output. Tarnab is essential to the management of these valuable resources (Rabnawaz et al. 2015). On the average, 1.9 billion m^3 of blue-water is consumed by major crops, demonstrating the substantial dependence of agricultural production on available water resources (Khan et al., 2021). Consequently, variability in temperature and precipitation, together with changes in other agro-meteorological conditions, can have important implications for crop water requirements, irrigation planning and agricultural productivity, highlighting the importance of local climate assessment for sustainable agricultural and water-resource management.

The objectives of this study were to (i) quantify seasonal and annual temperature patterns and rates of change during 2015–2025; (ii) describe the annual and seasonal distribution of rainfall and its reliability; and (iii) identify meteorological drought years and discuss implications for agriculture and water management.

2. Materials and methods

2.1 Study area

The study area is Agricuture Research Institute Tarnab Peshawar. The Agriculture Research Institute (ARI) Tarnab is located in the fertile Peshawar Valley at coordinates 34°13′12″N,

71°40′51″E, with an elevation of about 300–317 meters above sea level. It experiences a semi-arid to subtropical climate, supporting major crops such as wheat, sugarcane, vegetables, and fruit orchards, irrigated primarily by the Swat Canal and tubewells.

2.2 Data

Daily temperature and rainfall data for 2015–2025 were obtained from the meteorological station at Agriculture Research Institute (ARI), Tarnab Peshawar, Pakistan. Maximum and minimum air temperatures were recorded using a maximum/minimum thermometer installed in a Stevenson screen, while rainfall was measured using an ordinary manual rain gauge. The data were checked for consistency by comparison with the preceding and following days and with corresponding observations published by the Pakistan Meteorological Department (PMD), Peshawar. No missing observations were found during the study period. Daily temperature values were averaged, while rainfall values were summed to obtain monthly, seasonal and annual values, which were used for subsequent analysis and graphical presentation.

Seasons were defined as winter (January, February and December), spring (March–May), summer (June–August) and autumn (September–November).

2.3 Temperature analysis

Mean seasonal and annual temperatures were calculated for each year. The change over the study period was expressed as the difference between 2025 and 2015 values and as the change per year (difference divided by 10 years). Future increments were estimated by linear extrapolation of the observed rates and are illustrative only (Table 1).

The Hamed–Rao, (1998) modified Mann–Kendall test indicated no statistically significant monotonic trends in summer, winter, or annual mean temperatures during the study period. Kendall's (Mann, 1945; Kendall, 1975) tau values were negative for summer ($\tau = -0.2727$), winter ($\tau = -0.1091$), and annual temperature ($\tau = -0.2727$), indicating estimated downward tendencies. Sen's slope (Sen, 1968) estimates were −0.1057, −0.0357, and −0.0663 °C year^{-1} for summer, winter, and annual mean temperature, respectively. However, the corresponding Hamed–Rao modified p-values of 0.2758, 0.6962, and 0.2758 exceeded the 0.05 significance threshold. Thus, none of the observed downward tendencies was statistically significant, and the results do not establish a persistent monotonic temperature trend over the analyzed period.

2.4 Rainfall variability and drought

Seasonal and annual rainfall totals were calculated for each year. Seasonal reliability was expressed as the coefficient of variation (CV, %) = standard deviation / mean × 100 (Kendall and Stuart, 1977). Seasons were described as moderately erratic (CV ≈ 45%) to highly erratic (CV > 60%) relative to one another . Rainfall variability based on the coefficient of variation (CV) was classified as low (CV < 20%), moderate (20% < CV < 30%), high (30% < CV < 40%), very high (40% < CV < 70%), and extremely high (CV > 70%), following Garba and Udokpoh (2023).

Meteorological drought years were defined as years in which annual rainfall was below 75% (Svoboda and Fuchs, 2018) of the 2015–2025 mean (510.7 mm; threshold 383 mm) following the long-period-average approach described by WMO and GWP (2016). Because the record is only eleven years long, the mean is not a climatological normal, and the results describe the study period only.

3. Results

3.1 Seasonal and annual temperature

Mean winter temperature ranged from 10.04 °C (2019) to 13.95 °C (2016); and the coldest winters were in January of 2020 (8.03 °C). Mean summer temperature ranged from 29.80 °C (2020) to 32.76 °C (2019). While the hottest summer temperatures occurred in June 2016 (34.6 °C) followed by June 2025 (34.51 °C). Mean annual temperature ranged from 20.49 °C (2020) to 23.69 °C (2016); recent years (2024–2025) had averages above 22 °C, while 2020 and 2023 (21.86 °C) were the cooler years (Figure 2). Note: Previous winter means of 1-4 °C were the means of individual months of winter, not seasonal means

Between 2015 and 2025 mean summer temperature rose/declined by -0.54 °C (-0.05 °C yr^{-1}), mean winter temperature by 0.91 °C (0.09 °C yr^{-1}) and mean annual temperature by 0.57 °C (0.06 °C yr^{-1}) (Table 1). If these rates persisted, summer would get warm/cold by a further -0.54 °C in 10 years and -1.08 °C in 20 years, and winter and annual means by 0.91/1.82 °C and 0.60/1.20 °C, respectively (Table 2). Such linear projections from an eleven-year record carry large uncertainty and are shown only to illustrate the relative difference between seasons: such as the negative effect of temperature seen in the summers could point to this fact. This may not be the case for a large number of years (Table 3).

3.2 Annual and seasonal rainfall

Annual rainfall averaged 510.7 mm and ranged from 300.3 mm (2023) to 822.8 mm (2015) (Figure 3). Wet years were 2015, 2018 and 2024 (645.6 mm); dry years were 2023, 2016 and 2021. Cumulative 11-year totals were highest in July (1156.5 mm) and August (792.2 mm), with notable contributions in March and April; several months, particularly June, September and October, recorded zero rainfall in some years.

Rainfall showed a bimodal pattern with two wet windows, spring (March–May) and summer (June–August) (Figure 4). Summer rainfall peaked at 417.6 mm in 2018 but fell to 20 mm in 2020 (272 mm in 2019). Spring recorded the highest seasonal total of the study, 377 mm in 2024, and the lowest, 30.5 mm in 2022; spring rainfall equalled or exceeded summer rainfall in 2015, 2020 and 2024. Winter rainfall was low and variable, from 143.2 mm (2022) to 17.2 mm (2021), and fell from 110.1 mm in 2020 to 17.2 mm in 2021. Autumn rainfall was below 100 mm in seven of eleven years and was 0 mm in 2016. The wettest summer occurred in 2018, whereas the driest year, 2023, showed depressed rainfall in three of four seasons.

3.3 Rainfall reliability

Summer supplied the highest mean rainfall (204.2 mm) and was the least variable season (CV 45%). Spring (155.1 mm) was the most variable (CV 64%), followed by autumn (59%) and winter (58%) (Table 4). Thus the season that contributed substantial rainfall in several years (spring) was also the least predictable.

3.4 Meteorological drought

The long-period average annual rainfall was 510.7 mm, giving a 75% threshold of 383 mm. Three years fell below this threshold: 2023 (300.3 mm; 58.8% of the mean), 2016 (368.7 mm; 72.2%) and 2025 (376.1 mm; 73.6%). 2021 (391.5 mm; 76.7%) was marginally above it (Table 5). In 2023 summer (103.5 mm) and winter (27.2 mm) rainfall were both far below average, so neither monsoon-season nor winter rainfall compensated for the deficit. In 2021 all seasons were close to or below their means, except the autumn with 90.7 mm whereas its mean was 77.47 mm. The wet year 2024 (645.6 mm), driven by the anomalous spring (377 mm), was followed by the dry year 2025.

4. Discussion

4.1 Summer temperature trends

The dataset of summer exhibits a distinct intra-seasonal thermal gradient where heat accumulation peaks in June before systematically moderating by late August. This pattern tracks the broader sub-continental pre-monsoon cycle, where intense solar radiation

progressively yields to expanding cloud cover and sub-seasonal moisture dynamics (Ibrahim and Ahmad, 2025). The intense 2015–2019 warming block mirrors documented microclimate heating and escalating heat wave frequencies across district Peshawar (Gul et. al. 2025). To evaluate the overarching decadal trajectory, a modified Mann-Kendall trend test accounting for serial autocorrelation was applied to the 2015–2025 summer means.

The analysis confirmed that the overall cooling pattern is not statistically significant (Kendall's $\tau = -0.2727$), Hamed & Rao modified $p = 0.2758$, Sen's slope = -0.1057 °C/year), indicating a stable long-term baseline despite notable inter-annual variations. (Table: a)

4.2 Winter variability

The winter mean temperature dataset demonstrates a highly variable sub-seasonal thermal structure characterized by moderate, shifting fluctuations rather than a steep linear climate trend. Winter temperatures can vary considerably in association with large-scale atmospheric circulation and tropical ocean conditions (Karim et. al. 2023). The τ, p and Sen's slope suggest that the observed inter annual temperature fluctuations do not provide sufficient evidence of a consistent warming or cooling trend during the study period. In comparison, Nawaz et al. (2024) reported increasing trends in maximum and minimum temperatures in Peshawar over a longer observation period (1985–2022). The present analysis indicates that a significant winter mean temperature trend could not be established for short term variability, despite evidence of longer-term temperature changes in Peshawar. Continued monitoring using longer observational records would help clarify the direction and magnitude of winter temperature changes and their implications for local agricultural conditions.

4.3 Rainfall irregularity and seasonality

Rainfall was concentrated in the mid-year period and varied markedly between years, from 300.3 mm in 2023 to 822.8 mm in 2015. The spring maximum in 2024 (377 mm) may reflect enhanced pre-monsoon convective activity or late western disturbances, but this cannot be confirmed without circulation data. Heavy spring rain can interfere with the harvest of winter crops, whereas failure of a seasonal peak leaves little buffer: in 2018 and 2024 a single season delivered most of the annual total, which raises the risk of flash floods when it is intense and of drought when it fails. Months with zero rainfall indicate further irregularity in seasonal onset.

4.4 Temperature–rainfall relationship and drought

Warmer years did not consistently correspond with wetter or drier years, indicating that temperature and rainfall varied largely independently over this period. Higher temperatures combined with rainfall deficits can raise evaporative demand (Vicente-Serrano et al., 2010); this should be quantified with a Standardized Precipitation evapotranspiration-based index (SPEI) before conclusions on water balance are drawn. Successive seasons with below-average rainfall limit soil-moisture recovery and groundwater recharge (Freeze and Cherry, 1979), which may have implications for irrigation supply. Groundwater is particularly important for water supply in the Peshawar region, where previous studies have identified pressures associated with groundwater abstraction and changes in land use. Khan et al. (2017) estimated mean annual groundwater recharge of 269.1 mm from rainfall for Peshawar District during 2002–2011, whereas Khan et al. (2019) reported a decline in estimated precipitation-derived groundwater recharge from 108.75 mm yr^{-1} in 1981 to 91.35 mm yr^{-1} in 2014, alongside groundwater-table declines in some areas. However, because groundwater levels and recharge were not directly measured in the present study, the effects of the observed temperature and rainfall variability on groundwater storage and irrigation supply cannot be established from the meteorological data alone The alternation of a wet year (2024) and a dry year (2025) suggests that the region cannot rely on one wet year to recharge storage, but a longer record is needed to establish whether drought frequency is changing.

4.5 Implications for agriculture and water management

The observed warming trends have potential implications for crop heat stress and agricultural water requirements, as increasing temperatures can enhance evapotranspiration and increase crop water demand (Shafeeque and Bibi, 2023). In Pakistan, climate-related heat stress has been identified as a significant risk to crop productivity, highlighting the importance of heat-resilient cultivars and locally appropriate adaptation measures (Shafeeque and Bibi, 2023; Saddique et al., 2022). Rising temperatures and changing precipitation patterns pose to Pakistan's agricultural production and food security (Syed et al. 2022). In the present study, warmer summers may increase crop heat stress and water demand, while variable rainfall may complicate sowing decisions and irrigation planning. These findings highlight the importance of heat- and drought-tolerant varieties, adjusted sowing dates, efficient irrigation, rainwater harvesting, and seasonal climate early-warning systems.

4.6 Limitations

The record is short (eleven years), based on observations from a single meteorological station. The climate normal represents the mean of the study period rather than a standard 30-year climatological normal. Linear extrapolations are indicative only. Furthermore, crop, groundwater, and atmospheric circulation data were not analyzed; consequently, the potential agricultural and hydrological implications discussed here remain hypotheses requiring further investigation.

5. Conclusions

Between 2015 and 2025 summer temperature rose by 0.14 °C yr^{-1}, twice the rate of winter (0.07 °C yr^{-1}) and of the annual mean (0.06 °C yr^{-1}). Annual rainfall averaged 510.7 mm and varied between 300.3 and 822.8 mm; rainfall was bimodal, with spring the least reliable season (CV 64%) and summer the most reliable (CV 45%). Three years 2016, 2023 and 2025 with 368.7, 300.3 and 376.1 mm rainfall respectively fell below 75% of mean rainfall. These results indicate a shift toward hotter summers and more erratic rainfall that threatens water security and crop production. Longer records, formal trend tests and drought indices Standardized Precipitation Index (SPI) and SPEI are recommended for confirmation.

Declarations

Funding:

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of interest:

The authors declare that they have no conflict of interest.

Data availability:

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

author statement:

Farida Anjum; original drafting, review and supervising; Aamir Khan: Data curation, Visualization, second draft

Acknowledgements:

The authors acknowledge the Directorate of Soil and Plant Nutrition, Agriculture Research Institute (ARI), Tarnab, Peshawar, for providing access to the meteorological data used in this study and all possible resources make available to Agriculture system by the Khyber Pakhtunkhwa government.

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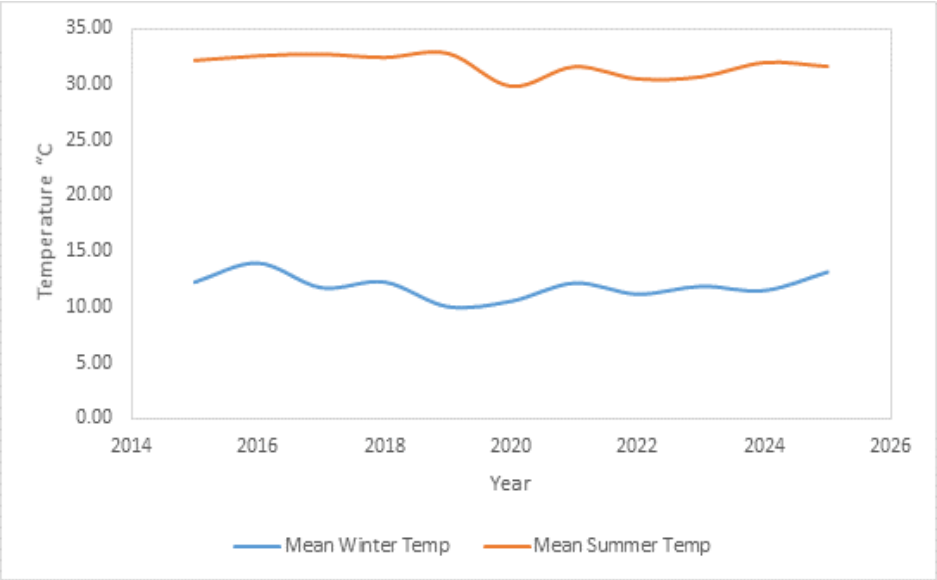

Figure 1. Mean summer (June–August) and winter (December–February) temperature, 2015–2025.

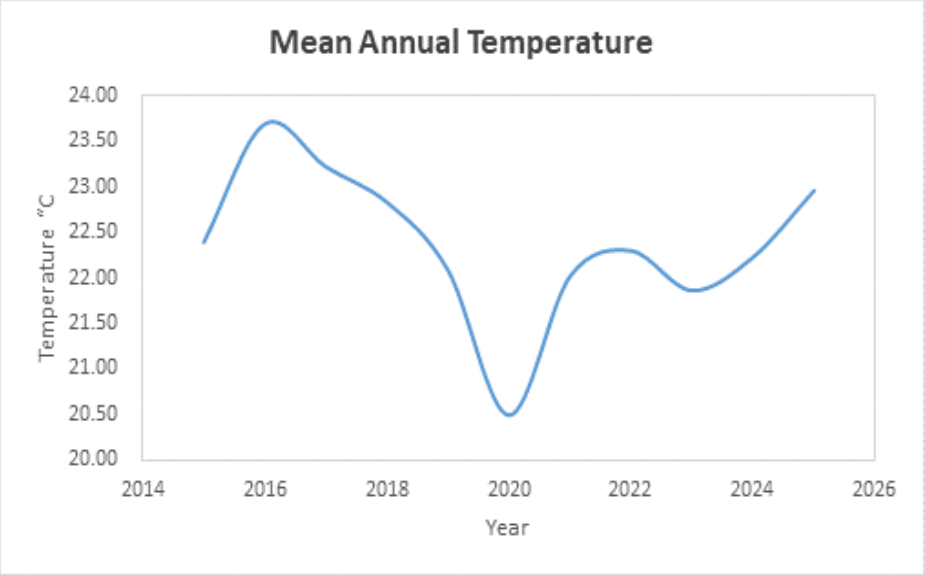

Figure 2. Mean annual temperature, 2015–2025.

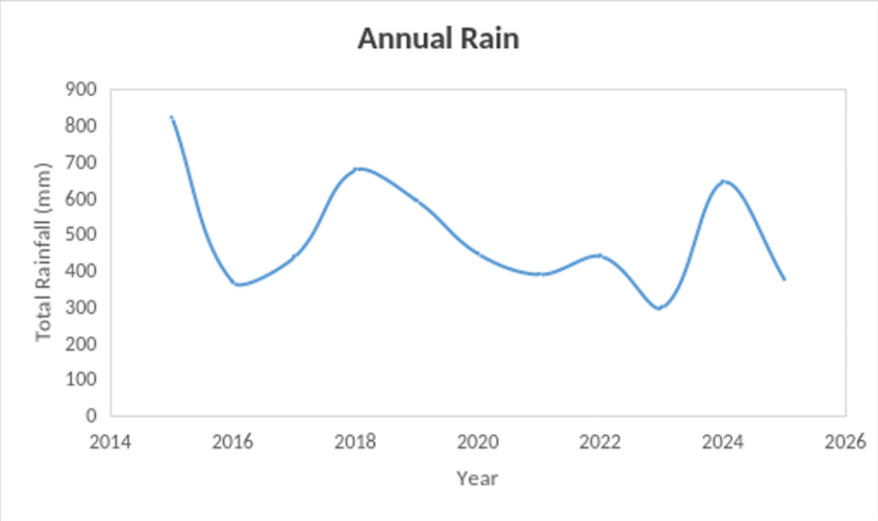

Figure 3. Total annual rainfall, 2015–2025.

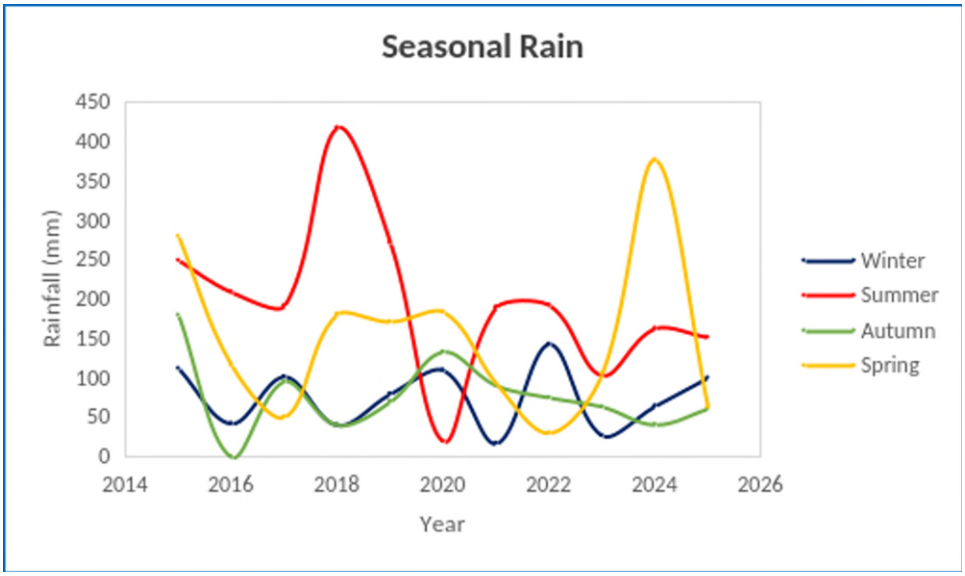

Figure 4. Seasonal rainfall, 2015–2025.

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