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*Research article*

# Long-term trends and variability of air temperature and precipitation across the Potwar Plateau region, northern Pakistan (1982–2022)

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**Abstract:** The Potwar Plateau region (PPR) is one of the most climate-sensitive areas of Pakistan, where variability in temperature and precipitation poses significant challenges to water resources and rain-fed agriculture. This study examined long-term trends and variability in annual mean temperature (Tmean) and total precipitation (PPT) over a 41-year period (1982–2022) using data from six meteorological stations. Data homogeneity was assessed using RHtestsV3, with log-transformed precipitation data to ensure consistency and reliability. Trend detection was performed using the nonparametric Mann–Kendall test and Sen's slope estimator, while spatial patterns were analyzed through ordinary kriging in ArcGIS. Hydroclimatic variability and dry-wet conditions were further evaluated using the Standardized Precipitation Anomaly (SPA) index. The results revealed pronounced seasonal temperature variability, with January minima ranging from 5.57 °C (Chakwal) to 12.45 °C (Jhelum), and June maxima ranging from 30.09 °C (Murree) to 35.2 °C (Jhelum). However, long-term temperature trends remained weak and statistically insignificant, as indicated by Attock ($\beta = -0.016$ °C/year, $p = 0.221$). In contrast, precipitation exhibited substantial spatial and temporal variability, with annual totals ranging from approximately 200 to over 3300 mm; July was consistently identified as the wettest month across all stations. A statistically significant increasing trend in precipitation was observed at Attock ($\beta = 15.688$ mm/year, $p = 0.003$), while other stations showed nonsignificant positive trends. SPA analysis indicated alternating phases of near-normal, mildly dry, and wet conditions, with a prolonged period of mild dryness from the mid-1990s to around 2015, followed by a short but intense wet phase during 2018–2021. Negative anomalies generally

remain within moderate ranges and do not indicate severe drought conditions. Overall, the findings highlight increasing hydroclimatic variability rather than a consistent long-term trend, emphasizing growing uncertainty in precipitation patterns. These results underscore the need for improved climate monitoring, adaptive water resource management, and region-specific resilience strategies in the Potwar Plateau region.

**Keywords:** climate change; temperature trends; precipitation extremes; Mann-Kendall test; Potwar plateau

## 1. Introduction

Climate change is increasingly recognized as one of the most significant global challenges of the 21st century, with profound implications for ecological systems, water resources, and socioeconomic development [1,2]. According to the Intergovernmental Panel on Climate Change (IPCC), the global mean surface temperature increased by approximately 0.85 °C between 1880 and 2012, primarily due to anthropogenic greenhouse gas emissions (IPCC, 2014) [3]. Although extreme weather events such as floods, droughts, and heatwaves are statistically infrequent, their frequency, intensity, and persistence have risen in recent decades, exerting disproportionate impacts on both human and natural systems [4,5]. These extremes threaten environmental stability, water and food security, public health, and infrastructure, particularly in developing countries with limited adaptive capacity. Precipitation and temperature extremes are critical indicators of climate variability and serve as early warnings of longer-term climate shifts [6,7].

The IPCC projects an increase in the occurrence and severity of climate extremes across all regions, with particularly serious implications for low- and middle-income countries (IPCC, 2021). South Asia, with its complex monsoon systems and densely populated river basins, is highly vulnerable [5]. Fluctuations in rainfall patterns, coupled with rising temperatures, have already begun to disrupt water availability, agricultural productivity, and disaster preparedness across the region. Pakistan exemplifies this vulnerability [8,9]. Positioned at the intersection of the South Asian monsoon and western weather systems, the country is increasingly exposed to climate-induced hazards such as prolonged droughts, record-breaking heatwaves, and catastrophic floods [8,10]. The 2010 floods, which inundated approximately 20% of Pakistan's land area and displaced nearly 20 million people, resulted in damages estimated at USD 10 billion, primarily in the agricultural sector [11,12]. In addition to flooding, Pakistan has experienced severe temperature-related extremes, including prolonged heatwaves and drought episodes, which have intensified water scarcity and agricultural stress, particularly in semi-arid regions [13]. Between 1999 and 2018, Pakistan consistently ranked among the top five countries most affected by climate change, highlighting the urgent need for localized climate assessments to inform resilience strategies [12,14].

Despite increasing research on climate change in Pakistan, much of it remains concentrated at national or provincial scales, leaving mesoscale and ecologically sensitive regions under-examined. One such region is the Potwar Plateau in northern Pakistan [15,16]. This transitional zone between the Himalayan foothills and the arid plains of Punjab is characterized by complex topography, semi-arid conditions, and dual influences from both the southwest monsoon and western disturbances [17,18]. The region exhibits pronounced spatial variability in temperature and precipitation due to elevation gradients,

with high-altitude areas such as Murree experiencing cooler temperatures and higher precipitation, while lowland areas such as Attock and Chakwal are comparatively warmer and drier [19]. This heterogeneity makes the Potwar Plateau a critical natural laboratory for understanding localized climate responses to global warming [20]. The Plateau plays a crucial role in the Upper Indus River system and supports a mix of rain-fed agriculture, dryland farming, and small-scale irrigation. However, recent climate variability has posed significant risks to water availability, soil moisture retention, and food production in the region [1,2].

Historically, the region and its surroundings have been affected by multiple climate-related disasters, highlighting their vulnerability. For instance, major flood events in 1950, 1973, 1992, 1998, 2010, and 2022 caused widespread damage, with affected populations reaching millions, and economic losses exceeding USD 1 billion. Similarly, extreme climatic variability has contributed to drought conditions and thermal stress in recent decades, exacerbating hydrological instability [21–23]. These recurring hazards underscore the sensitivity of the region to both precipitation variability and temperature fluctuations. While national studies highlight rising aridity and shifting precipitation patterns, localized assessments in Potwar remain scarce, undermining policymakers' and communities' ability to implement effective adaptation strategies [24,25].

This study addresses that gap by analyzing long-term trends (1982–2022) in temperature and precipitation variability across the Potwar Plateau using high-resolution climate data. The specific objectives are to (i) quantify temporal trends in temperature and rainfall, (ii) evaluate seasonal and annual variability, and (iii) identify emerging risks to water security and agricultural resilience. The findings provide crucial insights into the evolving hydro-meteorological behavior of the Potwar Plateau and serve as a baseline for engineers, water managers, and policymakers in designing climate-resilient infrastructure, irrigation systems, and conservation strategies. By linking localized climate variability with documented disaster impacts, this study strengthens the understanding of how regional climate behavior contributes to broader climate risk patterns under global warming.

## 2. Materials and methods

### *2.1. Study area*

The Potwar Plateau is located in northern Pakistan between latitudes 32°30'N and 34°00'N and longitudes 71°45'E and 73°45'E (Figure 1). It is geographically bounded by the Indus River to the west and the Jhelum River to the east, forming a transitional zone between the Himalayan foothills and the Punjab plains [26]. The landscape consists of undulating hills, valleys, and ridges, with elevations ranging from 300 to 1000 meters above sea level. The region features a semi-arid climate with subtropical highland influences, governed by both the southwest monsoon and western disturbances. Summer temperatures (May–September) typically range from 30 to over 40 °C, while winter temperatures (December–February) drop to between 4 and 10 °C [27]. Annual precipitation ranges from 500 to 1500 mm, with most rainfall concentrated during the monsoon season (July–September). Recent climatic shifts, including increased frequency of extreme temperatures and uneven rainfall distribution, have had significant effects on agriculture, water availability, and biodiversity [7,28].

To assess climatic variability across this heterogeneous landscape, six key meteorological stations (Attock, Chakwal, Jhelum, Islamabad, Murree, and Rawalpindi) have been utilized [29]. These stations provide long-term data on temperature and precipitation, enabling localized trend analysis [30]. Murree

represents high-altitude climatic conditions; Chakwal and Attock reflect semi-arid agricultural zones; Islamabad and Rawalpindi offer insights into urban climate dynamics; and Jhelum captures the eastern riverine environment [31]. Physiographically, the Plateau's loamy soils support dryland and rain-fed agriculture, primarily wheat, barley, and orchard crops [32]. The region is also rich in natural resources such as limestone, coal, and rock salt. Surrounding features, including the Margalla Hills and Himalayan foothills to the north, the Salt Range to the south, and major river systems on both flanks, significantly influence the region's climate, hydrology, and land-use patterns [30]. These characteristics make the Potwar Plateau a strategically important but underexplored region for studying long-term hydroclimatic trends in Pakistan [33,34].

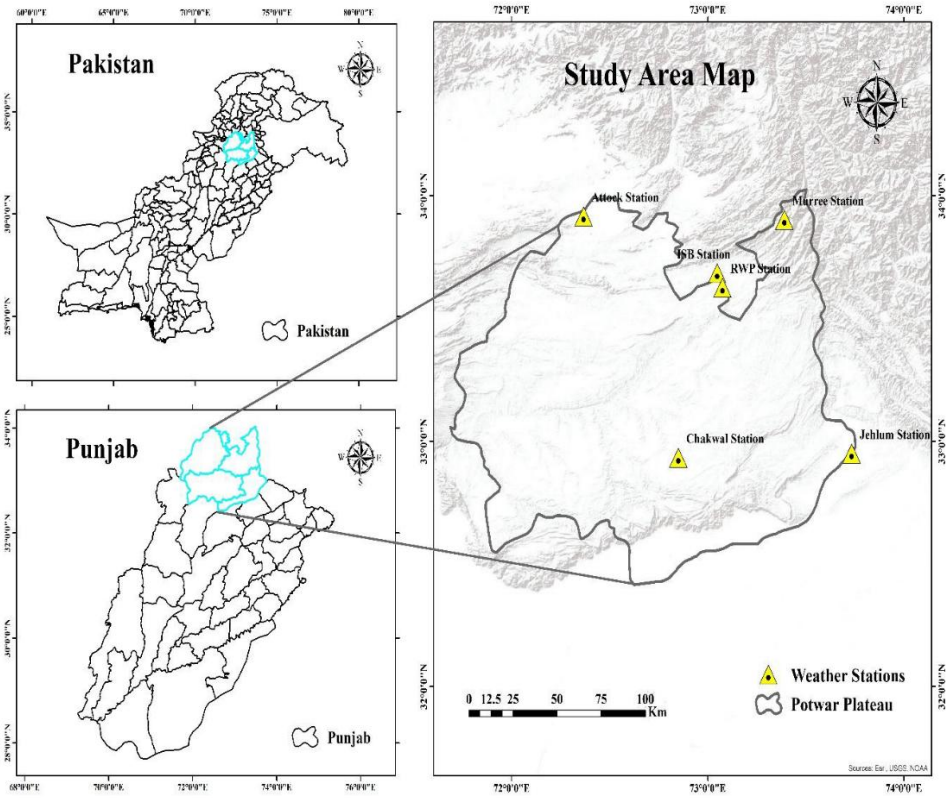



**Figure 1.** Study area map of the Potwar Plateau, Pakistan, illustrating its geographical location within the country and Punjab province. The map highlights the spatial distribution of six meteorological stations (Attock, Chakwal, Jhelum, Islamabad, Murree, and Rawalpindi) used in this study. Elevation variations across the plateau are also depicted, emphasizing the region's complex topography and its influence on local climate patterns.

### *2.2. Data*

Monthly mean air temperature and total precipitation data for the Potwar Plateau region over 41 years (1982–2022) may be obtained from global data repositories such as the National Oceanic and Atmospheric Administration (NOAA), particularly through datasets like NOAAGlobalTemp (available at https://www.ncei.noaa.gov/products/land-based-station/noaa-global-temp). These datasets provide reliable, standardized climate records that can support comprehensive analyses of temperature and precipitation variability in the study area. Detailed information on these stations,

including their geographic coordinates, elevation, and climatic characteristics, is presented in Figure 1 and Table 1. Station selection was based on their spatial distribution across the plateau and the availability of consistent, long-term datasets suitable for climate trend analysis [35]. To facilitate temporal assessment, monthly precipitation values were aggregated to generate annual totals, while monthly temperature values were averaged to compute annual mean temperatures [36]. The primary focus of the analysis was to identify long-term trends in temperature and precipitation at each station. Additionally, interstation comparisons were conducted, particularly for precipitation data, to explore spatial variability and regional coherence across the plateau [37].

**Table 1.** List of meteorological stations in the Potwar Plateau region, northern Pakistan. Geographical coordinates (longitude and latitude), altitude, and data type [temperature (Tem) and precipitation (Preci)] are provided. All stations were used for the analysis of climate variability and extremes in the study area.

| Station name | Longitude (°E) | Latitude (°N) | Altitude (m) | Data type |
|---|---|---|---|---|
| Attock Station | 72.3667 | 33.9167 | 212 m | Tem, Preci |
| Chakwal Station | 72.8500 | 32.9333 | 508 m | Tem, Preci |
| ISB Station | 73.0479 | 33.6844 | 507 m | Tem, Preci |
| Jhelum Station | 73.7333 | 32.9500 | 247 m | Tem, Preci |
| Murree Station | 73.3908 | 33.9025 | 2,291m | Tem, Preci |
| RWP Station | 73.0748 | 33.6259 | 518 m | Tem, Preci |

### *2.3. Methods*

To evaluate long-term climate variability across the Potwar Plateau region (PPR) from 1982 to 2022, both monotonic and abrupt (step) trends were analyzed. Monotonic trends, indicating consistent increases or decreases over time, were assessed using the Mann–Kendall test, a nonparametric method robust to non-normal distributions and missing values [38]. The magnitude of trends was estimated using Sen's slope estimator, which is resistant to the influence of outliers. To account for serial correlation in the time series, we applied the iterative pre-whitening procedure proposed by before conducting the trend analysis. All statistical analyses were performed in R [39] using the $trend$, $Kendall$, and $Zyp$ packages. This nonparametric test compares the distributions of two groups (pre- and post-change point) without assuming normality. Homogeneity testing was conducted using the $RHtestsV3$ software, with log-transformed precipitation data to improve statistical robustness [40,41].

To assess field significance, i.e., whether observed local trends are regionally coherent, we employed a Monte Carlo simulation approach. For each climate variable, 1000 simulations were conducted. In each iteration, the time series at each spatial grid point was randomly permuted while preserving the spatial structure of the dataset [42]. Mann–Kendall Z-statistics were recalculated for each permutation. If the proportion of grid points with statistically significant trends ($p < 0.05$) in the observed data exceeded the 95th percentile of the simulated distribution, the trend was considered field-significant. Spatial patterns of climate trends were visualized using ordinary Kriging interpolation, implemented in both ArcGIS Pro and the $gstat$ package in R [43]. This geo-statistical method accounts for both spatial proximity and autocorrelation, enabling the generation of continuous trend surfaces for temperature and precipitation across the PPR [44].

## 3. Results

### *3.1. Spatio-temporal patterns of air temperature in the Potwar Plateau region, Pakistan*

The long-term dynamics of air temperature across the Potwar Plateau were examined using observations from six meteorological stations, with the analysis standardized over the common period of 1982–2022 to ensure consistency and comparability among sites [29]. Although minor differences existed in data availability, rigorous data quality control and completeness checks were performed before analysis, thereby ensuring the reliability of the results [45]. The assessment was conducted at both temporal (monthly and annual) and spatial scales, enabling a comprehensive evaluation of temperature variability across the region [46]. Figure 2 illustrates the distribution of monthly average temperatures, highlighting clear spatial contrasts that are largely influenced by elevation and geographic setting.

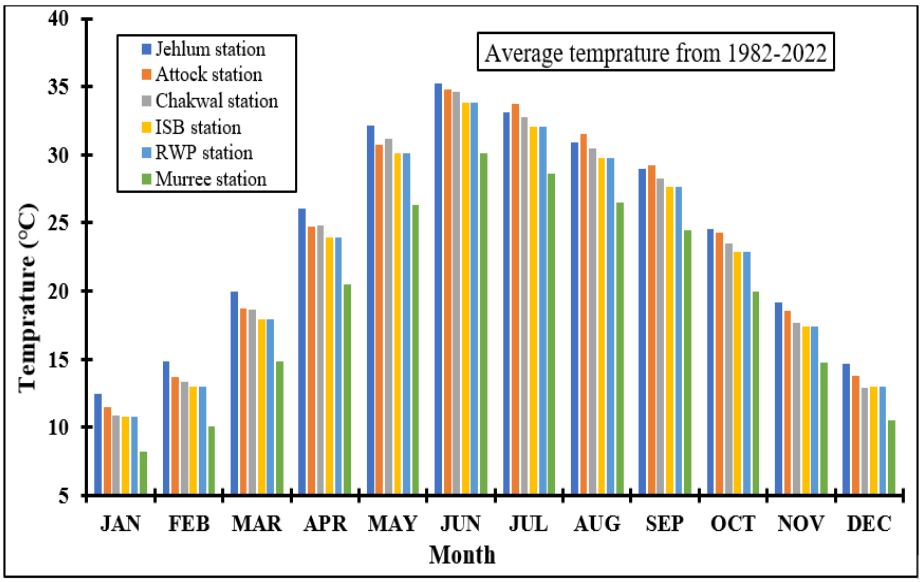



**Figure 2.** Monthly average temperatures for six stations in the Potwar Plateau (1982–2022). Temperatures rise from winter to a peak in June–July and decline toward December. Murree remains cooler due to its higher elevation, while other stations show similar seasonal patterns.

The results indicate that Jhelum consistently records the highest mean monthly temperatures, with a pronounced peak in June (35.2 ± 0.8 °C), which can be attributed to its low elevation (233 m above sea level) and inland location that favors heat accumulation [47]. A similar seasonal pattern is observed at other stations, where maximum temperatures also occur in June, including Attock (34.8 °C), Chakwal (34.7 °C), and Islamabad and Rawalpindi (33.8 °C), reflecting the regional influence of continental heating during the pre-monsoon period [48]. In contrast, Murree, located at a substantially higher elevation (2291 m), exhibits significantly lower temperatures, with a June average of 30.1 °C, thereby demonstrating the strong moderating effect of altitude. Seasonal variability is comparatively reduced during the winter months, particularly January and December, when temperatures reach their annual minima; notably, Murree records the lowest January average (8.2 °C), whereas the remaining stations range between 10.8 °C and 12.5 °C [49]. These patterns collectively underscore the dominant

role of elevation, continentality, and seasonal atmospheric processes in shaping the temperature regime of the Potwar Plateau [50].

*3.2. Descriptive statistics and temperature seasonal variability across the Potwar Plateau*

**Table 2.** Monthly minimum, mean, and maximum temperature (°C), along with standard deviation, for six meteorological stations in the Potwar Plateau (1982–2022). The data highlight clear seasonal patterns, with the lowest temperatures in winter (January) and the highest values in summer (June–July). Standard deviation values indicate increased variability during the pre-monsoon period, particularly in May, across all stations.

| Station name | Month | Minimum | Maximum | Mean | Std. deviation |
|---|---|---|---|---|---|
| **Attock** | January | 9.000 | 13.890 | 11.501 | 1.206 |
| | February | 10.370 | 17.480 | 13.665 | 1.631 |
| | March | 14.470 | 24.060 | 18.710 | 2.049 |
| | April | 20.590 | 28.810 | 24.732 | 1.898 |
| | May | 26.370 | 34.870 | 30.760 | 2.238 |
| | June | 29.350 | 37.320 | 34.812 | 1.493 |
| | July | 29.690 | 37.100 | 33.699 | 1.643 |
| | August | 28.850 | 34.570 | 31.522 | 1.617 |
| | September | 26.860 | 32.500 | 29.229 | 1.413 |
| | October | 22.550 | 26.250 | 24.322 | 1.043 |
| | November | 15.580 | 20.230 | 18.531 | 1.073 |
| | December | 11.590 | 17.230 | 13.748 | 1.326 |
| **Chakwal** | January | 5.570 | 10.660 | 8.208 | 1.259 |
| | February | 6.990 | 14.150 | 10.063 | 1.660 |
| | March | 11.020 | 19.780 | 14.809 | 1.951 |
| | April | 16.410 | 24.290 | 20.501 | 1.894 |
| | May | 21.740 | 30.730 | 26.336 | 2.253 |
| | June | 25.200 | 32.470 | 30.088 | 1.408 |
| | July | 25.610 | 32.080 | 28.605 | 1.466 |
| | August | 24.690 | 29.370 | 26.525 | 1.323 |
| | September | 21.960 | 27.260 | 24.503 | 1.247 |
| | October | 18.460 | 22.480 | 19.976 | 1.084 |
| | November | 12.180 | 16.560 | 14.718 | 1.022 |
| | December | 8.340 | 14.170 | 10.491 | 1.369 |
| **Islamabad** | January | 8.620 | 13.230 | 10.803 | 1.197 |
| | February | 9.800 | 16.910 | 12.995 | 1.574 |
| | March | 13.880 | 22.870 | 17.920 | 1.993 |
| | April | 19.610 | 28.260 | 23.933 | 2.065 |
| | May | 24.610 | 34.350 | 30.156 | 2.377 |
| | June | 28.080 | 35.970 | 33.832 | 1.555 |
| | July | 28.660 | 35.860 | 32.030 | 1.613 |

*Continued on next page*

| | Month | Minimum | Maximum | Mean | Std. deviation |
|---|---|---|---|---|---|
| | August | 27.610 | 32.950 | 29.757 | 1.489 |
| | September | 25.080 | 30.870 | 27.619 | 1.538 |
| | October | 21.090 | 25.730 | 22.910 | 1.245 |
| | November | 14.810 | 19.420 | 17.391 | 1.094 |
| | December | 10.890 | 16.480 | 12.969 | 1.312 |
| **Jhelum** | January | 10.300 | 14.600 | 12.471 | 1.108 |
| | February | 11.480 | 19.090 | 14.828 | 1.572 |
| | March | 15.550 | 24.590 | 19.958 | 2.042 |
| | April | 21.510 | 29.980 | 26.051 | 2.053 |
| | May | 26.190 | 35.550 | 32.114 | 2.177 |
| | June | 30.030 | 36.960 | 35.197 | 1.418 |
| | July | 29.750 | 36.650 | 33.121 | 1.552 |
| | August | 28.620 | 34.900 | 30.902 | 1.436 |
| | September | 26.640 | 32.300 | 28.986 | 1.411 |
| | October | 22.870 | 27.230 | 24.537 | 1.090 |
| | November | 17.050 | 20.900 | 19.186 | 0.998 |
| | December | 12.450 | 17.910 | 14.662 | 1.232 |
| **Murree** | January | 5.570 | 10.660 | 8.208 | 1.259 |
| | February | 6.990 | 14.150 | 10.063 | 1.660 |
| | March | 11.020 | 19.780 | 14.809 | 1.951 |
| | April | 16.410 | 24.290 | 20.501 | 1.894 |
| | May | 21.740 | 30.730 | 26.336 | 2.253 |
| | June | 25.200 | 32.470 | 30.088 | 1.408 |
| | July | 25.610 | 32.080 | 28.605 | 1.466 |
| | August | 24.690 | 29.370 | 26.525 | 1.323 |
| | September | 21.960 | 27.260 | 24.503 | 1.247 |
| | October | 18.460 | 22.480 | 19.976 | 1.084 |
| | November | 12.180 | 16.560 | 14.718 | 1.022 |
| | December | 8.340 | 14.170 | 10.491 | 1.369 |
| **Rawalpindi** | January | 8.620 | 13.230 | 10.803 | 1.197 |
| | February | 9.800 | 16.910 | 12.995 | 1.574 |
| | March | 13.880 | 22.870 | 17.920 | 1.993 |
| | April | 19.610 | 28.260 | 23.933 | 2.065 |
| | May | 24.610 | 34.350 | 30.156 | 2.377 |
| | June | 28.080 | 35.970 | 33.832 | 1.555 |
| | July | 28.660 | 35.860 | 32.030 | 1.613 |
| | August | 27.610 | 32.950 | 29.757 | 1.489 |
| | September | 25.080 | 30.870 | 27.619 | 1.538 |
| | October | 21.090 | 25.730 | 22.910 | 1.245 |
| | November | 14.810 | 19.420 | 17.391 | 1.094 |
| | December | 10.890 | 16.480 | 12.969 | 1.312 |

A comprehensive summary of the minimum, mean, and maximum monthly temperatures, along with their corresponding standard deviations for six meteorological stations in the Potwar Plateau from 1982 to 2022, is presented in Table 2, providing insight into both seasonal patterns and regional variability [51]. The results indicate a well-defined seasonal cycle, with January consistently recording the lowest minimum temperatures, reflecting the peak of winter conditions; for instance, Chakwal and Murree both report minima of 5.57 °C, whereas Attock exhibits relatively warmer conditions at 9.0 °C, likely due to its lower elevation and geographic setting [46]. In contrast, the summer months (June–July) represent the warmest period, with Jhelum recording the highest mean temperature in June (35.2 °C), which can be attributed to its low elevation (233 m) and inland location that enhances heat accumulation [52]. Similarly, maximum temperatures peak during June across most stations, including Attock (37.32 °C) and Islamabad and Rawalpindi (35.97 °C), while Murree records comparatively lower maxima (30.09 °C), reflecting the moderating influence of higher elevation [53].

In addition to seasonal contrasts, the analysis highlights notable intra-annual temperature variability, as indicated by standard deviation values, which are consistently highest during the pre-monsoon month of May across all stations [31]. For example, Islamabad and Rawalpindi exhibit the greatest variability (2.377 °C), whereas Chakwal and Murree show similarly elevated fluctuations (2.25 °C), suggesting enhanced atmospheric instability and transitional climatic conditions during this period. This increased variability likely results from the interaction of continental heating, pre-monsoonal convection, and shifting synoptic systems, which contribute to greater temperature fluctuations before the onset of the monsoon [54]. These findings reflect the characteristics of a continental climate regime in northern Pakistan, marked by hot summers, cool winters, and pronounced seasonal and diurnal variability, and they underscore the importance of temperature dynamics for agricultural productivity, water resource management, and climate adaptation planning in the Potwar Plateau [55].

### *3.3. Annual mean temperature trends and variability in the Potwar Plateau region*

The linear regression trends of mean annual temperatures from 1982 to 2022 across six meteorological stations (Attock, Chakwal, Islamabad, Jhelum, Murree, and Rawalpindi) are presented in Figure 3, capturing both the magnitude of interannual variability and the direction of long-term temperature changes in the Potwar Plateau [56]. Although considerable year-to-year fluctuations are evident in the temperature records, linear regression was applied to quantify potential long-term trends; however, the results consistently indicate only marginal declining tendencies at all stations, none of which attain statistical significance [57]. This is clearly reflected in the very low coefficients of determination ($R^2$ values ranging from 0.0016 to 0.0453), suggesting that the temporal component explains only a minimal fraction of the observed variability [58]. For instance, Attock exhibits the most pronounced decline with a regression slope of −0.016 °C year$^{-1}$ ($R^2$ = 0.0453), while Chakwal and Murree both show very slight decreases of −0.0029 °C year$^{-1}$ ($R^2$ = 0.0016). Similarly, Islamabad records a modest negative trend (−0.0071 °C year$^{-1}$, $R^2$ = 0.0077), whereas Rawalpindi follows a nearly identical pattern, and Jhelum shows the weakest decline (−0.0013 °C year$^{-1}$, $R^2$ = 0.004), collectively demonstrating a consistent but weak downward tendency across the region [59].

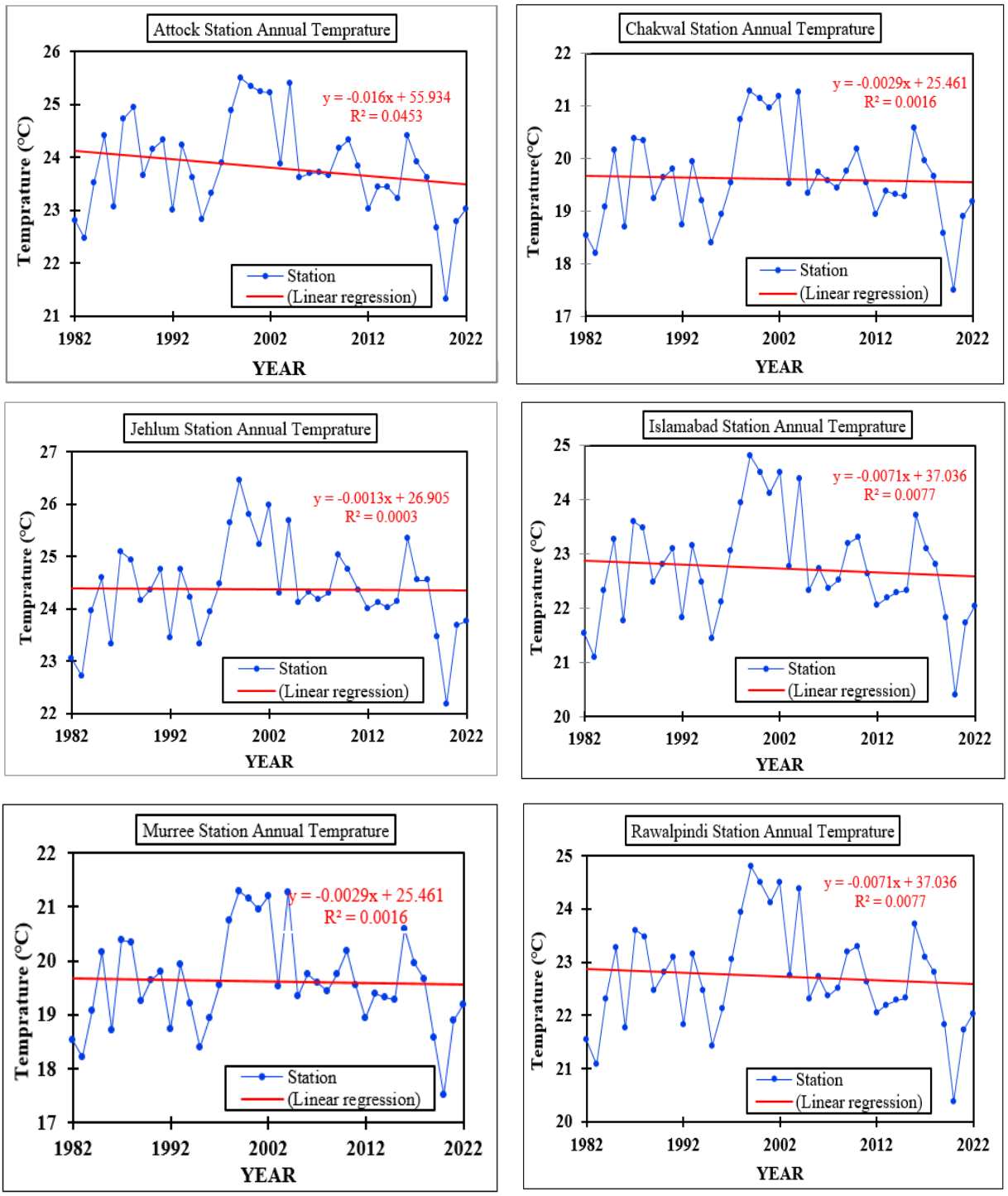



**Figure 3.** Annual mean temperature variations for six meteorological stations (Attock, Chakwal, Jhelum, Islamabad, Murree, and Rawalpindi) in the Potwar Plateau region from 1982 to 2022. Linear regression lines show slight declining trends at all stations with very low $R^2$ values, indicating weak relationships. Overall, the figure reflects notable interannual variability and no statistically significant long-term temperature trends across the study area.

These results strongly suggest that there is no statistically meaningful linear trend in annual mean temperatures at any of the stations over the 41-year study period, despite the presence of observable interannual fluctuations [58]. The persistently low $R^2$ values indicate that a substantial proportion of temperature variability remains unexplained by time alone, thereby implying that other controlling factors such as natural climate variability, local topographic influences, and potential urban heat island effects in rapidly urbanizing areas like Islamabad and Rawalpindi likely play a more dominant role in shaping the observed temperature patterns [60]. Furthermore, the uniformity of weak and nonsignificant trends across all stations suggests that regional-scale warming or cooling signals are either absent or too subtle to be captured through simple linear regression techniques [61]. Consequently, these findings highlight the need for more robust analytical approaches, including nonparametric trend detection methods (e.g., Mann–Kendall and Sen's slope) and seasonally disaggregated analyses, which may provide deeper insights into underlying climatic changes and help identify subtle shifts that are otherwise masked within annual aggregates [62].

### *3.4. Sen's slope (β) and Mann–Kendall (p) trend analysis of annual mean temperature in the Potwar Plateau*

**Table 3.** Magnitude of trends (Sen's slope, β) and Mann–Kendall (MK) test results (p-values) for annual mean temperature. Results are presented for all meteorological stations in the Potwar Plateau region. Analysis covers the period from 1982 to 2022.

| **Annual temperature** | | |
|---|---|---|
| **Station name** | **Sen's slope (β)** | **MK test (p)** |
| Attock | −0.019 | 0.221 |
| Chakwal | −0.004 | 0.857 |
| ISB | −0.010 | 0.515 |
| Jhelum | −0.003 | 0.805 |
| Murree | −0.004 | 0.857 |
| RWP | −0.032 | 1.000 |

Sen's slope (β) and the corresponding Mann–Kendall (MK) p-values, which indicate the direction, magnitude, and statistical significance of annual mean temperature trends from 1982 to 2022 across six meteorological stations in the Potwar Plateau region, are presented in Table 3. All stations exhibit negative Sen's slope values, suggesting slight downward trends; however, none were statistically significant at the 95% confidence level ($p > 0.05$) [63]. Attock station showed the steepest decline ($\beta = -0.019$ °C year, $p = 0.221$), while Rawalpindi also exhibited a modest negative trend ($\beta = -0.032$ °C year), though its MK p-value of 1.000 indicates no statistical significance. Similarly, Chakwal ($\beta = -0.004$, $p = 0.857$), Murree ($\beta = -0.004$, $p = 0.857$), and Jhelum ($\beta = -0.003$, $p = 0.805$) displayed minimal decreases, lacking any statistical support [64]. Islamabad's trend ($\beta = -0.010$ °C year, $p = 0.515$) was likewise nonsignificant. Overall, the analysis indicates no significant long-term warming or cooling trends in annual mean temperatures across the region. The weak trends and low significance levels suggest that observed interannual variations may be due to short-term fluctuations or inherent climate variability rather than persistent directional changes [65]. These

findings underscore the need for seasonal or extreme-value analyses to capture subtler climate dynamics potentially obscured in annual aggregates.

### *3.5. Spatial distribution and elevation-controlled variability of annual mean temperature in the Potwar Plateau*

The spatial distribution of mean annual temperatures across the Potwar Plateau from 1982 to 2022 consistently reflects a clear elevation-driven gradient, with cooler temperatures prevailing at higher altitudes. Specifically, the northeastern high-elevation region, including Murree station, consistently recorded the lowest mean temperatures, while the southwestern lowland stations, such as Attock and Chakwal, exhibited relatively higher annual averages [66]. This pattern remained stable throughout the study period, as illustrated by decadal analyses (Figure 4a–d) and corroborated by preliminary 2022 observations (Figure 4e). Long-term trend analyses using linear regression (Figure 3) revealed marginal declines in mean annual temperatures at all six meteorological stations, with slopes ranging from −0.0029 to −0.016 °C/year; however, these trends were not statistically significant, as evidenced by low coefficients of determination ($R^2$ values between 0.0016 and 0.0453) [67].

Similarly, nonparametric Sen's slope estimates (Table 3) confirmed slight negative trends across all stations (β values from −0.003 to −0.032 °C/year), none reaching significance at the 95% confidence level ($p > 0.05$). For example, Attock exhibited the steepest, yet nonsignificant, decline ($\beta = -0.019$ °C/year, $p = 0.221$), while Rawalpindi showed a minimal trend with a nonsignificant p-value of 1.000. These results indicate that, despite subtle downward tendencies in annual mean temperatures, no statistically meaningful long-term warming or cooling trends exist across the Potwar Plateau during these 41 years [68,69]. The persistent temperature elevation gradient (Pearson's $r = -0.87$, $p < 0.01$) highlights topography as the dominant factor shaping spatial temperature patterns, while the weak temporal trends and low significance levels suggest that interannual variability and local factors, such as microclimate effects and land-use changes, may largely drive observed fluctuations [70]. Future investigations employing seasonal or extreme-event analyses may better elucidate finer-scale climatic changes potentially masked in annual mean values.

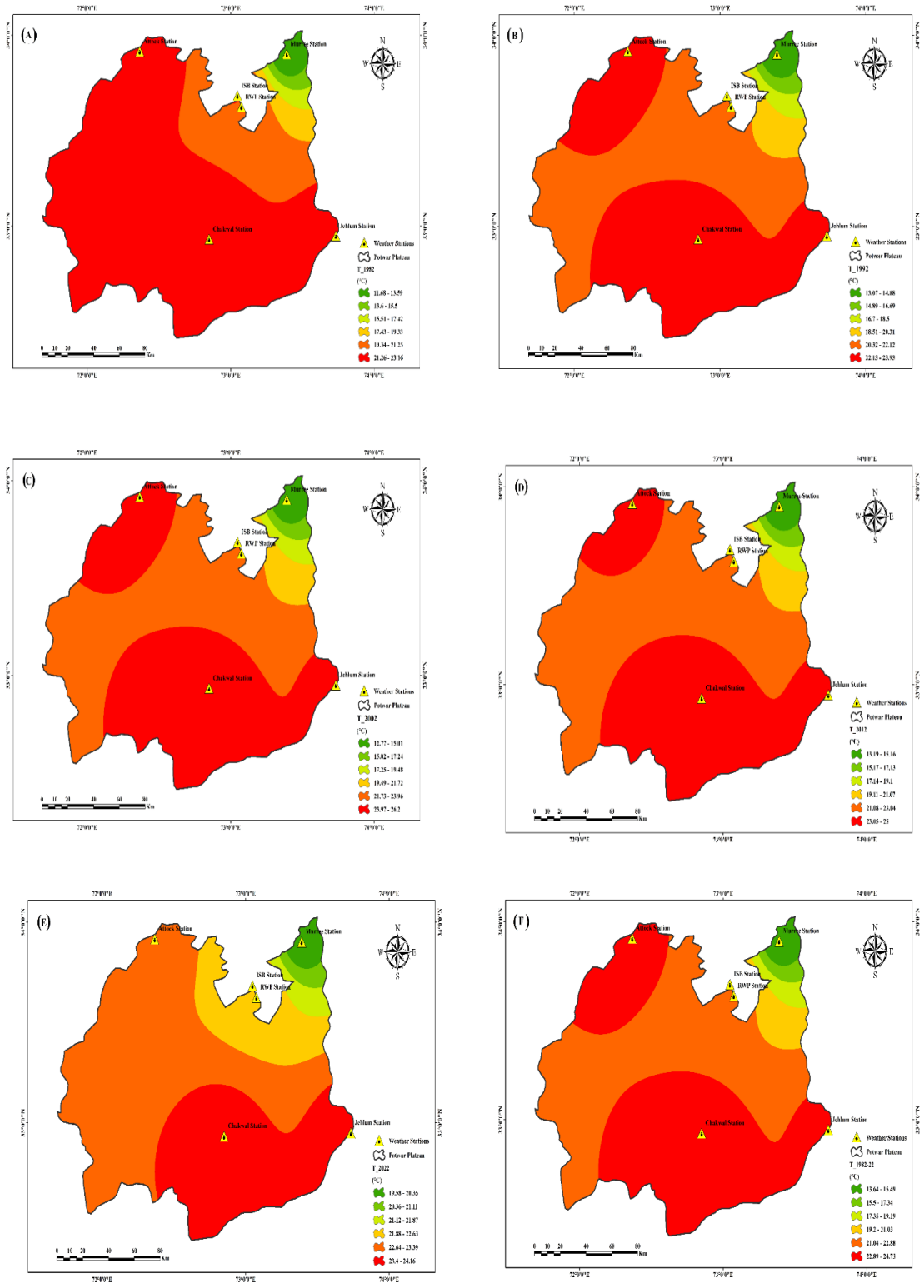



**Figure 4.** Spatial distribution of mean annual temperature across the Potwar Plateau, Pakistan, for multiple periods: (a) 1982–1992, (b) 1992–2002, (c) 2002–2012, (d) 2012–2022, (e) 2022 onward, and (f) 1998–2022. Cooler conditions persist in the northeastern highlands (Murree), while warmer temperatures dominate the southwestern lowlands (Attock and Chakwal). Meteorological stations (Attock, Chakwal, Islamabad, Jhelum, Murree, and Rawalpindi) are shown, highlighting a stable elevation-driven temperature pattern.

## 4. Comprehensive analysis of precipitation variability and trends in the Potwar Plateau

Precipitation is a key climatic parameter influencing hydrological processes, agricultural systems, and climate variability across the Potwar Plateau. Similar to temperature, precipitation exhibits notable spatial and temporal variability due to the combined effects of regional atmospheric circulation and local topographic controls [71]. To ensure consistency with the temperature analysis, precipitation was evaluated at monthly, annual, and spatial scales using descriptive statistics, linear regression, Sen's slope estimator, and the Mann–Kendall test for trend detection over the period 1982–2022 [72]. The analysis focuses on six meteorological stations (Attock, Chakwal, Islamabad, Jhelum, Murree, and Rawalpindi) to assess seasonal patterns, interannual variability, and long-term trends. Monthly analysis captures the dominant monsoonal precipitation regime, while annual and trend-based analyses provide insights into variability and directional changes. In addition, standardized precipitation anomalies (SPA) were used to identify drought and wet periods, and spatial interpolation techniques were applied to examine the geographical distribution of precipitation across the plateau [73]. This approach ensures methodological consistency with the temperature analysis and enables a comprehensive evaluation of precipitation dynamics in the region. The results highlight the influence of monsoon systems, western disturbances, and elevation gradients, while also capturing variability and emerging changes in precipitation behavior [74,75]. Such integrated analysis is essential for understanding hydroclimatic conditions and supporting water resource management and climate adaptation strategies in the Potwar Plateau.

### *4.1. Seasonal characteristics and precipitation monthly variability in the Potwar Plateau*

Monthly average precipitation across the Potwar Plateau from 1982 to 2022 exhibits a distinct seasonal pattern, characterized by peak rainfall during the summer monsoon months (July–August), as shown in Figure 5. Among all stations, Jhelum recorded the highest average July precipitation (204.74 mm), followed by Islamabad and Rawalpindi (202.76 mm), Chakwal (188.05 mm), Murree (185.00 mm), and Attock (120.08 mm) [76]. This peak is attributed to the southwest monsoon system, which dominates the regional rainfall regime. In contrast, the lowest monthly precipitation totals were observed during the winter and post-monsoon months (October and December), with values generally below 20 mm across all stations [77]. The precipitation pattern was broadly consistent among stations, except during July and August, when Jhelum consistently received markedly higher rainfall, likely due to localized orographic enhancement and convective storm activity. The pronounced summer rainfall concentration reflects the influence of a monsoonal climate, rather than a maritime regime, with over 60% of annual precipitation occurring between June and September [78]. These findings align with previous hydro-meteorological studies in the region and underscore the vulnerability of the Potwar Plateau to seasonal flooding, particularly under intensifying monsoon extremes. Further analysis incorporating trend detection techniques and event-based precipitation indices may provide deeper insights into long-term variability and its implications for water resource management and flood risk in the region [79].

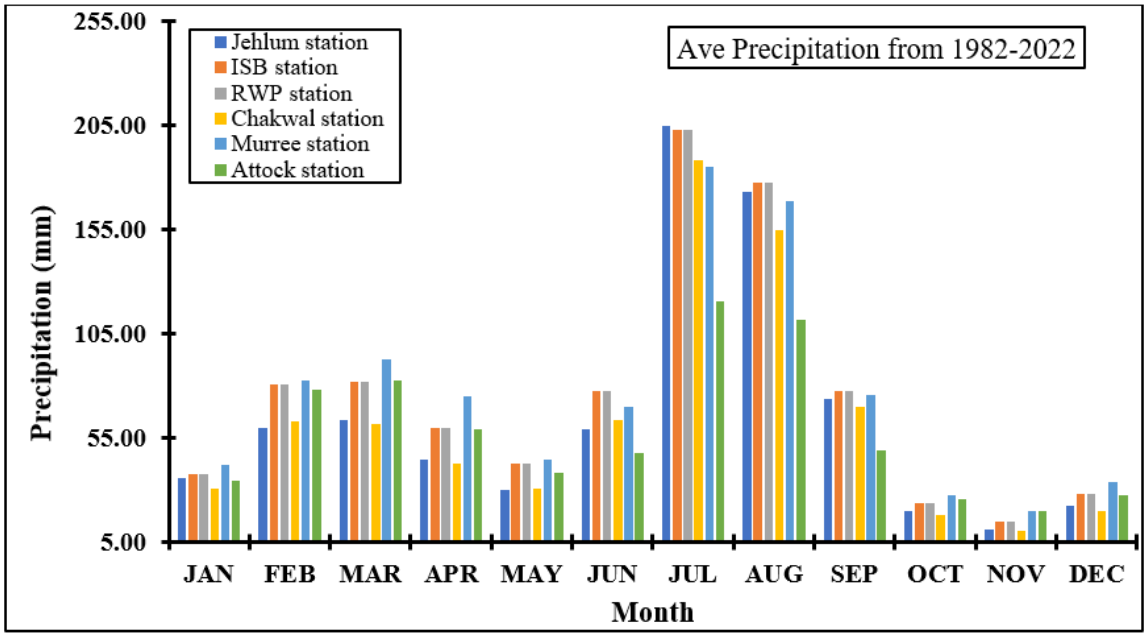



**Figure 5.** Average monthly precipitation at six meteorological stations (Jhelum, Islamabad, Rawalpindi, Chakwal, Murree, and Attock) in the Potwar Plateau region. Precipitation exhibits strong seasonal variability, with peaks during the monsoon months and lower values in winter. Murree generally records higher precipitation due to elevation, while other stations show relatively similar patterns.

*4.2. Descriptive statistics and spatio-temporal precipitation variability in the Potwar Plateau*

The minimum, mean, and maximum annual precipitation values, along with standard deviations, for six meteorological stations across the Potwar Plateau from 1982 to 2022 are presented in Table 4. Substantial interannual and monthly variability is evident, particularly during the summer monsoon season [80]. The highest monthly rainfall occurred in June, while July recorded the highest mean. Annual precipitation ranged from 200.39 to 3301.17 mm, with a mean of 697.15 mm. Chakwal exhibited a similar pattern, with June and July being the wettest months; notably, July recorded both the highest mean and minimum monthly rainfall. The annual average was 753.83 mm, with a range of 195.12 to 2863.48 mm [81]. In Islamabad, monsoon months (June, July, and August) dominated precipitation totals. July had the highest average, while August registered the highest minimum. Annual precipitation ranged from 226.76 to 3791.60 mm, with a mean of 905.79 mm. A nearly identical pattern was observed in Rawalpindi, likely due to the stations' close geographic proximity and shared climatic regime . At Jhelum, July emerged as the peak rainfall month, recording both the highest maximum and minimum values. The annual mean was 799.32 mm, with totals ranging from 205.66 to 2167.38 mm.

**Table 4.** Monthly minimum, maximum, and mean precipitation (mm), along with standard deviation, for all meteorological stations in the Potwar Plateau region. The data covers the period from 1982 to 2022.

| Station name | Month | Minimum | Maximum | Mean | Std. deviation |
|---|---|---|---|---|---|
| **Attock** | January | 0.000 | 171.840 | 34.802 | 39.003 |
| | February | 0.000 | 406.050 | 78.429 | 79.992 |
| | March | 0.000 | 485.160 | 82.657 | 79.881 |
| | April | 5.270 | 247.850 | 59.474 | 56.102 |
| | May | 0.000 | 453.520 | 38.627 | 70.425 |
| | June | 0.000 | 643.360 | 47.864 | 100.092 |
| | July | 5.270 | 421.640 | 120.836 | 103.057 |
| | August | 5.270 | 379.690 | 111.563 | 73.209 |
| | September | 0.000 | 199.990 | 49.317 | 45.297 |
| | October | 0.000 | 180.870 | 25.929 | 37.106 |
| | November | 0.000 | 116.020 | 20.009 | 27.814 |
| | December | 0.000 | 188.730 | 27.641 | 40.041 |
| **Chakwal** | January | 0.000 | 153.010 | 30.613 | 30.558 |
| | February | 0.000 | 427.150 | 62.888 | 84.791 |
| | March | 0.000 | 379.690 | 61.664 | 68.152 |
| | April | 0.000 | 195.120 | 42.571 | 43.586 |
| | May | 0.000 | 406.050 | 30.835 | 64.096 |
| | June | 0.000 | 748.830 | 63.540 | 117.286 |
| | July | 26.370 | 570.630 | 188.052 | 103.498 |
| | August | 21.090 | 363.870 | 154.990 | 77.612 |
| | September | 0.000 | 288.710 | 69.970 | 60.256 |
| | October | 0.000 | 115.550 | 18.171 | 21.584 |
| | November | 0.000 | 72.220 | 10.256 | 15.112 |
| | December | 0.000 | 79.100 | 20.279 | 23.210 |
| **Islamabad** | January | 0.000 | 174.720 | 37.960 | 37.672 |
| | February | 0.000 | 580.080 | 80.803 | 111.769 |
| | March | 0.000 | 485.160 | 82.122 | 82.967 |
| | April | 0.000 | 263.670 | 59.710 | 59.095 |
| | May | 0.000 | 580.080 | 42.658 | 90.882 |
| | June | 0.000 | 980.860 | 77.347 | 151.261 |
| | July | 31.640 | 579.030 | 202.757 | 116.769 |
| | August | 36.910 | 384.960 | 177.876 | 82.478 |
| | September | 0.000 | 250.450 | 77.644 | 61.176 |
| | October | 0.000 | 175.290 | 23.704 | 30.775 |
| | November | 0.000 | 100.200 | 14.991 | 22.266 |
| | December | 0.000 | 164.410 | 28.213 | 36.962 |

*Continued on next page*

| | Month | Minimum | Maximum | Mean | Std. deviation |
|---|---|---|---|---|---|
| **Jhelum** | January | 0.000 | 172.580 | 36.107 | 36.123 |
| | February | 0.000 | 274.220 | 59.922 | 61.249 |
| | March | 0.000 | 337.500 | 63.778 | 68.580 |
| | April | 0.000 | 210.940 | 44.452 | 44.112 |
| | May | 0.000 | 216.210 | 30.259 | 39.379 |
| | June | 0.000 | 374.410 | 59.469 | 65.853 |
| | July | 36.910 | 581.840 | 204.743 | 110.957 |
| | August | 31.640 | 432.420 | 173.012 | 85.321 |
| | September | 5.270 | 300.830 | 73.934 | 63.021 |
| | October | 0.000 | 107.100 | 19.956 | 22.443 |
| | November | 0.000 | 64.960 | 11.371 | 15.264 |
| | December | 0.000 | 68.550 | 22.310 | 24.842 |
| **Murree** | January | 0.000 | 176.570 | 41.992 | 40.629 |
| | February | 0.000 | 411.330 | 82.915 | 82.880 |
| | March | 0.000 | 479.880 | 92.607 | 81.218 |
| | April | 5.270 | 305.860 | 74.931 | 69.068 |
| | May | 5.270 | 448.240 | 44.723 | 71.764 |
| | June | 0.000 | 632.810 | 69.673 | 98.890 |
| | July | 15.820 | 532.620 | 185.002 | 107.516 |
| | August | 42.190 | 395.510 | 168.811 | 81.126 |
| | September | 0.000 | 237.300 | 75.980 | 57.774 |
| | October | 0.000 | 182.900 | 27.410 | 34.414 |
| | November | 0.000 | 121.290 | 19.675 | 28.169 |
| | December | 0.000 | 212.250 | 33.896 | 45.782 |
| **Rawalpindi** | January | 0.000 | 174.720 | 37.960 | 37.672 |
| | February | 0.000 | 580.080 | 80.803 | 111.769 |
| | March | 0.000 | 485.160 | 82.122 | 82.967 |
| | April | 0.000 | 263.670 | 59.710 | 59.095 |
| | May | 0.000 | 580.080 | 42.658 | 90.882 |
| | June | 0.000 | 980.860 | 77.347 | 151.261 |
| | July | 31.640 | 579.030 | 202.757 | 116.769 |
| | August | 36.910 | 384.960 | 177.876 | 82.478 |
| | September | 0.000 | 250.450 | 77.644 | 61.176 |
| | October | 0.000 | 175.290 | 23.704 | 30.775 |
| | November | 0.000 | 100.200 | 14.991 | 22.266 |
| | December | 0.000 | 164.410 | 28.213 | 36.962 |

In Murree, located at higher elevations, the strongest precipitation occurred in June and July, while August had the highest minimum monthly rainfall, indicating persistent late-monsoon contributions. Murree recorded the highest annual mean among all stations (917.62 mm), with values ranging between 284.77 and 3306.45 mm [82]. Collectively, all stations demonstrated pronounced intra- and interannual variability, with the bulk of precipitation concentrated in the summer monsoon season (June–September). These results underscore the dominant influence of the southwest monsoon

and localized orographic effects in shaping the precipitation dynamics across the Potwar Plateau [83]. The observed variability highlights the importance of localized hydrological planning and climate adaptation strategies, particularly in light of the potential intensification of monsoon extremes under future climate change scenarios.

### *4.3. Pearson correlation values of precipitation at different stations on the Potwar Plateau*

Table 5 presents the Pearson correlation coefficients for precipitation among six meteorological stations (Attock, Chakwal, Islamabad, Jhelum, Murree, and Rawalpindi) in the Potwar Plateau region of Pakistan [27]. The results indicate strong positive correlations, ranging from 0.900 to 0.989, between all station pairs. This high degree of correlation suggests that precipitation variability across the region is spatially coherent, with rainfall patterns responding similarly to regional-scale atmospheric processes. The strongest correlations are observed between geographically closer stations, particularly Islamabad and Rawalpindi (r = 1.000) and Chakwal with Islamabad and Rawalpindi (r = 0.989), reflecting their proximity and shared climatic conditions. Even stations with relatively different elevations, such as Murree, show consistently high correlations (≥0.937), indicating that although absolute precipitation amounts may vary due to orographic effects, the temporal distribution of rainfall remains synchronized across the plateau [45]. Collectively, these findings imply that precipitation in the Potwar Plateau is primarily controlled by large-scale weather systems, such as the southwest monsoon and western disturbances, leading to regionally consistent rainfall events. This strong spatial association is important for hydrological modeling, agricultural planning, and disaster risk management, as it suggests that precipitation extremes and anomalies are likely to impact the entire region simultaneously rather than occurring in isolation [84,85].

**Table 5.** Pearson correlation coefficients of precipitation among six meteorological stations in the Potwar Plateau region. Strong positive correlations (0.900–0.989) indicate high spatial coherence of rainfall patterns across the region. Results suggest precipitation is largely controlled by common large-scale weather systems such as the monsoon and western disturbances.

| | Attock station | Chakwal station | Islamabad station | Jhelum station | Murree station | Rawalpindi station |
|---|---|---|---|---|---|---|
| Attock station | 1 | | | | | |
| Chakwal station | 0.952 | 1 | | | | |
| Islamabad station | 0.966 | 0.989 | 1 | | | |
| Jhelum station | 0.900 | 0.962 | 0.934 | 1 | | |
| Murree station | 0.956 | 0.970 | 0.987 | 0.937 | 1 | |
| RWP station | 0.966 | 0.989 | 1 | 0.934 | 0.987 | 1 |

*4.4. Assessment of annual precipitation trends using linear regression in the Potwar Plateau*

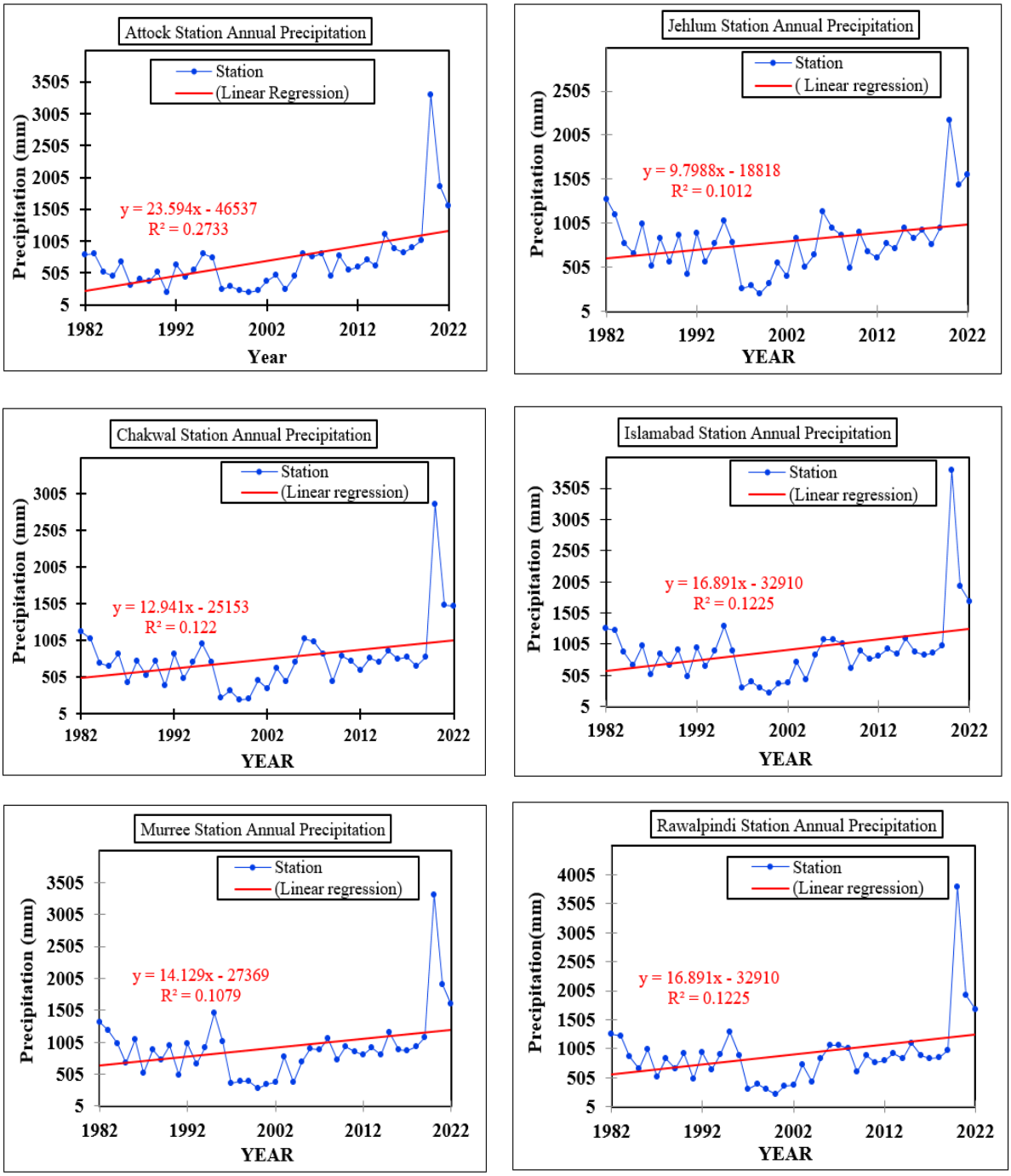



**Figure 6.** Linear regression of annual precipitation at six meteorological stations (Attock, Chakwal, Jhelum, Islamabad, Murree, and Rawalpindi) from 1982 to 2022. The results show high interannual variability with generally weak trends, as indicated by low $R^2$ values. A noticeable increase in precipitation is observed after 2015, with a regional peak in 2021 across all stations.

The temporal evolution of annual precipitation across six meteorological stations in the Potwar Plateau from 1982 to 2022 is illustrated in Figure 6, highlighting both interannual variability and potential long-term trends in regional rainfall behavior. The results demonstrate pronounced year-to-year fluctuations, with a distinct and spatially coherent regional peak in 2021 observed across all stations, indicating a widespread extreme precipitation event [86]. Although linear regression was employed to assess long-term tendencies, the analysis reveals weak relationships, as reflected by low coefficients of determination ($R^2$ = 0.1012–0.2733), suggesting that time alone explains only a small fraction of the observed precipitation variability [87]. Station-wise analysis shows largely consistent patterns, with Attock exhibiting the strongest, yet still weak, trend ($R^2$ = 0.2733), while Jhelum displays the lowest explanatory power ($R^2$ = 0.1012). In addition, Islamabad and Rawalpindi demonstrate nearly identical temporal behavior, reflecting their close geographic proximity and shared climatic controls, whereas Murree shows a slight increasing tendency, likely influenced by orographic effects, although the trend remains statistically weak [60]. Further examination of temporal patterns indicates a predominantly irregular and weakly declining phase from 1982 to 2015, characterized by considerable variability and the absence of a clear directional trend. This phase is followed by a coherent and region-wide upward shift in precipitation after 2015, culminating in the pronounced maximum observed in 2021, which is consistently reflected across all stations [88]. The transition from a weakly declining regime to a period of intensified precipitation suggests a potential shift in regional precipitation dynamics, possibly associated with enhanced monsoonal activity or broader climatic variability. Despite the limited statistical strength of the regression models, the synchronized increase across all stations provides compelling evidence of an emerging regional signal that warrants further attention [27].

The analysis indicates that precipitation in the Potwar Plateau is dominated by strong interannual variability and weak linear trends ($R^2$ = 0.1012–0.2733); however, the recent and consistent increase in precipitation after 2015, culminating in the 2021 peak, suggests a potential intensification of rainfall regimes across the region [89]. These findings highlight the limitations of linear trend analysis in capturing complex hydroclimatic behavior and emphasize the need for seasonal-scale and extreme-event investigations to better understand evolving precipitation patterns and their implications for climate variability, water resources, and hazards management.

### *4.5. Trend analysis of annual precipitation using Sen's slope and Mann–Kendall test in the Potwar Plateau*

Table 6 summarizes the results of Sen's slope (β) and the Mann–Kendall (MK) test applied to annual precipitation series across six meteorological stations in the Potwar Plateau for the period 1982–2022. The analysis indicates a general increasing tendency in precipitation at all stations, with Sen's slope values ranging from 5.383 to 15.688 mm/year [90]. However, statistical significance is observed only at Attock station (β = 15.688 mm/year, p = 0.004), indicating a robust and consistent upward trend in annual precipitation over the study period. All other stations exhibit positive but statistically nonsignificant trends, including Chakwal (β = 5.383, p = 0.129), Islamabad and Rawalpindi (β = 8.118, p = 0.154), Jhelum (β = 7.031, p = 0.132), and Murree (β = 7.277, p = 0.181) [91]. The relatively higher slope at Attock suggests a more pronounced increase in precipitation intensity or frequency, while the moderate slopes at other stations reflect weaker and more variable upward tendencies. The lack of statistical significance across most locations highlights the influence of strong interannual variability and spatial heterogeneity, which likely obscures consistent long-term trends [92].

**Table 6.** Sen's slope (β) and Mann–Kendall (MK) test (p-values) for annual precipitation trends at six stations in the Potwar Plateau (1982–2022). All stations show positive trends (β = 5.383–15.688 mm/year), with statistical significance observed only at Attock. Results indicate increasing precipitation tendencies with strong spatial variability and generally weak statistical significance.

| **Annual precipitation** | | |
|---|---|---|
| **Station name** | **Sen's slope (β)** | **MK test (p)** |
| Attock | 15.688 | 0.004 |
| Chakwal | 5.383 | 0.129 |
| Islamabad | 8.118 | 0.154 |
| Jhelum | 7.031 | 0.132 |
| Murree | 7.277 | 0.181 |
| RWP | 8.118 | 0.154 |

These results suggest that, while precipitation across the Potwar Plateau is generally increasing, the trend is not uniform or statistically robust across the region. The significant increase at Attock may indicate localized climatic or hydrological changes, whereas the broader pattern points to emerging but still uncertain shifts in precipitation regimes, potentially linked to variability in monsoonal dynamics [93]. These findings emphasize the need for seasonal-scale and extreme-event analyses to better capture underlying changes in precipitation behavior under evolving climate conditions.

### *4.6. Temporal variability and intensification of drought based on standardized precipitation anomalies in the Potwar Plateau*

Standardized precipitation anomalies (SPA) for six stations in the Potwar Plateau from 1982 to 2022 are presented in Figure 7, illustrating clear temporal variability in precipitation patterns. During the early period (1982–1990), SPA values at most stations fluctuated near zero, generally within ±0.5, indicating relatively stable and near-normal precipitation conditions with only minor wet and dry variations [94]. A shift toward negative anomalies is observed during 1995–2005, where most stations exhibit values ranging between −0.3 and −0.8 [95]. These values suggest mild to moderate dry conditions, rather than severe drought, with occasional positive anomalies interrupting the pattern. From 2005 to 2015, the anomalies remained predominantly negative but less pronounced, typically between −0.2 and −0.6, indicating continued but relatively moderate dryness across the region [96]. A notable transition occurs after 2018, when all stations record strong positive anomalies, reflecting wetter-than-normal conditions. The most prominent peak appears around 2020–2021, with SPA values reaching approximately 1.5 to 2.0 at several stations, particularly Rawalpindi, Chakwal, and Islamabad, indicating significantly wet conditions [97].

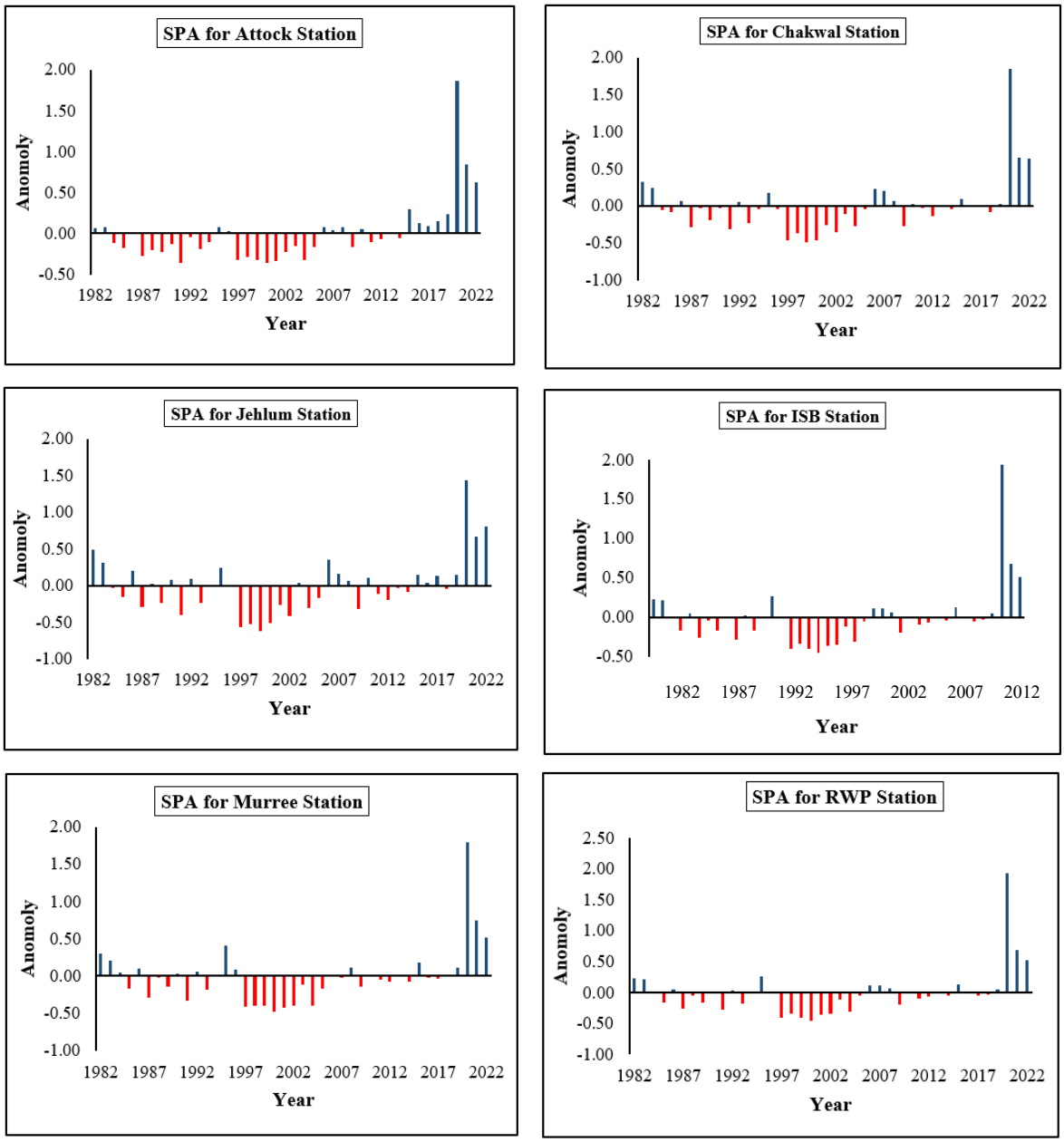



**Figure 7.** Standardized precipitation anomalies (SPA) for six stations in the Potwar Plateau from 1982 to 2022. Negative anomalies dominate after 2000, indicating increasing drought frequency and persistence across the region. The most severe drought conditions were observed in 2022, reflecting a shift toward intensified hydroclimatic stress.

However, in 2022, a decline in anomalies is observed at some stations, suggesting a return to variability in precipitation patterns. Collectively, the SPA series demonstrates alternating phases of relatively dry and wet conditions, with a prolonged period of mild dryness (1995–2015) followed by a short but intense wet phase (2018–2021). These findings indicate that precipitation variability in the Potwar Plateau is characterized by multi-decadal fluctuations rather than a consistent long-term drying trend [98]. The observed pattern suggests increasing variability, with shifts between moderately dry conditions and episodic wet events, highlighting the dynamic nature of hydroclimatic conditions in the region.

*4.7. Spatial distribution of precipitation in the Potwar Plateau under changing climate conditions*

The spatial distribution of annual precipitation across the Potwar Plateau (Figure 8A-F) reveals a persistent northwest-southeast gradient, strongly governed by orographic controls and regional atmospheric circulation, alongside pronounced temporal variability during 1982–2022. In the early period (1982–1992), precipitation ranged from approximately 786 to >1300 mm, with the highest values concentrated in the northeastern highlands (Murree region) [99]. This is consistent with station-based observations, where Murree recorded a mean annual precipitation of approximately 918 mm, significantly higher than lower-elevation stations such as Attock (697 mm). This decade was characterized by relatively stable hydroclimatic conditions and a clear elevation-dependent rainfall pattern. A marked decline in precipitation intensity occurred during 1992–2002, with spatial values decreasing to approximately 638–970 mm, particularly across central and southern parts of the plateau [100]. This dry phase is supported by regression analysis showing weak or negligible trends ($R^2$ as low as 0.1012) and extremely low annual totals, such as 200 mm at Attock during drought years. The consistency between spatial patterns and SPA results confirms a region-wide reduction in precipitation during this period. Between 2002 and 2012, precipitation exhibited partial recovery and spatial reorganization, with mean annual rainfall at stations such as Chakwal reaching approximately 754 mm [101]. A notable feature during this period is the emergence of a localized rainfall "bullseye" around Chakwal, indicating enhanced convective precipitation activity, deviating from the previously dominant elevation-controlled pattern [102]. Although Sen's slope estimates were positive (e.g., Chakwal $\beta$ = 5.383 mm/year, $p$ = 0.129), these trends remained statistically nonsignificant, reflecting continued variability.

The most recent period (2012–2022) is characterized by renewed intensification of precipitation, particularly after 2015, culminating in a regional peak in 2021 across all stations. High-elevation areas maintained dominance, with Murree recording extreme annual totals exceeding 3300 mm, while mid- and low-elevation stations such as Islamabad averaged around ~900 mm annually [103]. Importantly, Attock exhibited the only statistically significant increasing trend ($\beta \approx 15.7$ mm/year, $p = 0.003$), indicating a notable shift in precipitation behavior in traditionally drier western regions. Concurrently, the Chakwal-centered rainfall core intensified, further highlighting localized variability and spatial heterogeneity [104]. The results demonstrate that precipitation dynamics in the Potwar Plateau are controlled by a dual mechanism: persistent orographic forcing and evolving climatic variability. While the elevation-driven gradient remains stable, the region has undergone a clear multi-decadal transition, from relatively stable conditions in the 1980s to a prolonged dry phase (1990s to early 2000s), followed by localized convective intensification (2000s) and a recent phase of increased precipitation (post-2015) [105]. The coexistence of extended drought periods (as indicated by SPA) and recent extreme wet events underscores increasing hydroclimatic instability. These analyses suggest that the Potwar Plateau is experiencing a shift toward greater precipitation variability and intensification, likely linked to changes in monsoonal dynamics and broader regional climate forcing [106]. The emergence of spatially heterogeneous rainfall patterns, including localized hotspots and significant trends at specific stations, highlights the need for location-specific climate adaptation strategies. This has critical implications for water resource management, agricultural planning, and flood risk mitigation, particularly under future climate change scenarios where precipitation extremes are expected to intensify [107].

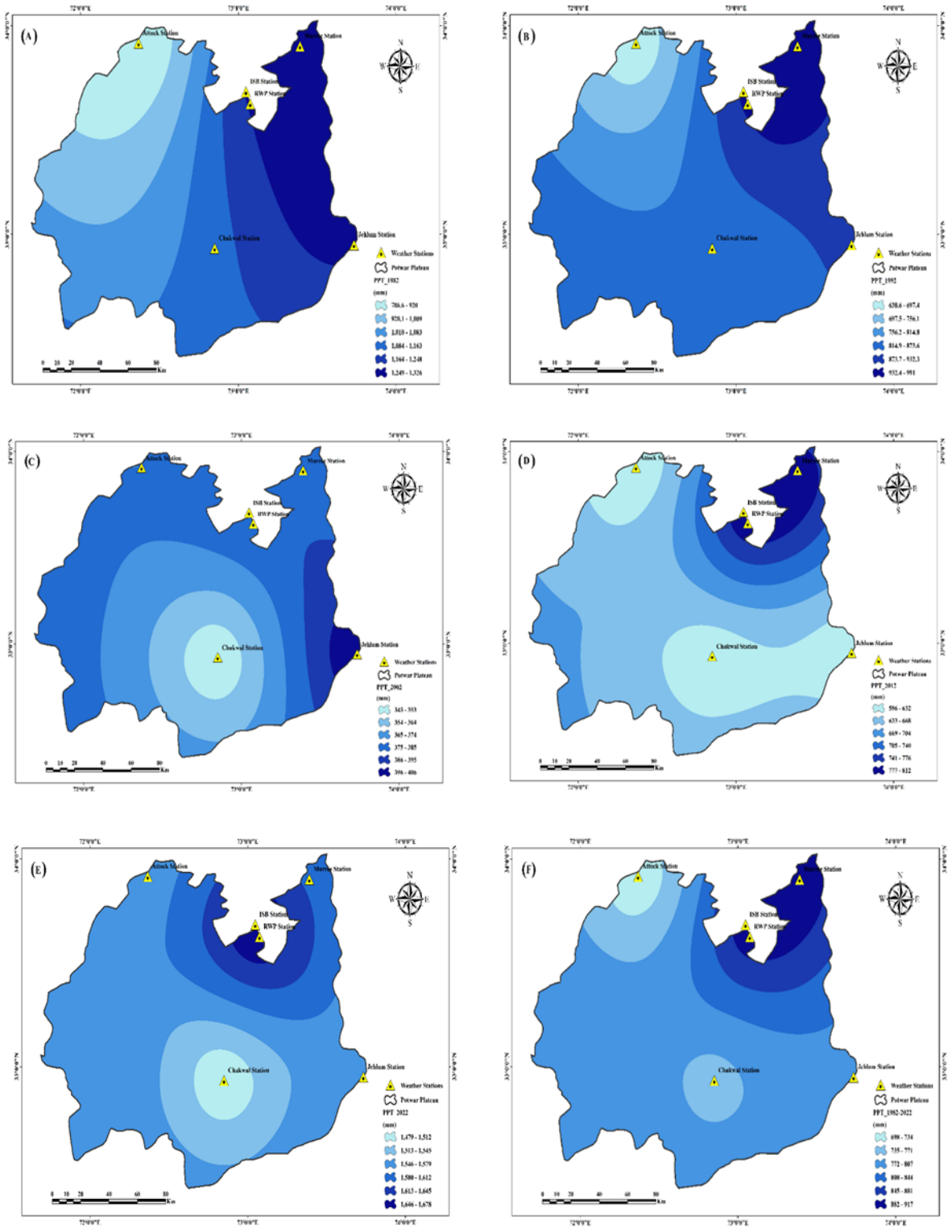



**Figure 8.** Spatial distribution of annual precipitation across the Potwar Plateau for multiple periods: (a) 1982–1992, (b) 1992–2002, (c) 2002–2012, (d) 2012–2022, (e) 2022 onward, and (f) 1998–2022. Precipitation shows a strong elevation-controlled pattern, with higher values in the northeastern highlands (Murree) and lower amounts in the southwestern lowlands. The maps highlight substantial temporal variability and recent intensification of precipitation, particularly after 2015, across all stations.

## 5. Discussion

This study examined long-term air temperature and precipitation variability across the Potwar Plateau from 1982 to 2022, providing important insights into the region's climatic behavior under the combined influence of topography and monsoonal systems. The climate of the Potwar Plateau is distinctly continental, characterized by hot summers and cold winters, with clear modulation by elevation. June consistently emerged as the warmest month across all stations, with maximum mean temperatures reaching 35.2 °C in Jhelum and 30.09 °C in Murree, whereas January represented the coldest period, with Murree recording a minimum of 8.21 °C and Chakwal the lowest overall temperature at 5.57 °C [108,109]. These spatial differences clearly reflect the influence of altitude on thermal distribution across the region. Seasonal transitions further contribute to temperature variability, with monthly fluctuations peaking in May, particularly in Islamabad and Rawalpindi (2.377 °C), indicating strong transitional dynamics between spring and summer. However, despite these pronounced seasonal variations, long-term temperature trends remain weak and statistically insignificant. Sen's slope estimates indicate slight negative trends in Attock ($\beta = -0.019$ °C/year, $p = 0.221$) and Islamabad ($\beta = -0.010$ °C/year, $p = 0.515$), while very low coefficients of determination (e.g., Chakwal $R^2 = 0.0016$) suggest that temporal changes explain only a minimal proportion of temperature variability [110,111]. This indicates that the thermal regime over the 40 years has remained relatively stable, with interannual variability playing a more dominant role than any consistent long-term warming or cooling signal.

In contrast, precipitation exhibits substantially greater variability both spatially and temporally, largely governed by monsoonal dynamics and topographic influences. July consistently recorded the highest monthly rainfall across all stations, with a peak of 204.74 mm in Jhelum and values exceeding 200 mm in Islamabad and Rawalpindi [112]. At the same time, notable intra-month variability is evident, as demonstrated by Chakwal receiving as little as 10.26 mm during July. Annual precipitation totals show a wide range, from approximately 200 to over 3300 mm, with Murree and Chakwal experiencing localized maxima, likely due to orographic uplift and convective processes associated with elevated terrain [27,113]. Although interannual variability dominates precipitation behavior, trend analysis reveals modest but spatially variable tendencies. Attock exhibits a statistically significant increasing trend ($\beta = 15.688$ mm/year, $p = 0.003$), while other stations, including Chakwal ($\beta = 5.383$ mm/year, $p = 0.129$) and Jhelum ($\beta = 7.031$ mm/year, $p = 0.132$), show positive but nonsignificant trends [114]. These patterns suggest a gradual intensification of precipitation, particularly in localized areas, although strong year-to-year fluctuations obscure the emergence of a consistent long-term signal. The occurrence of peak precipitation in 2021 across multiple stations further highlights the role of large-scale atmospheric processes in generating synchronized extreme rainfall events across the plateau [49].

Importantly, the observed variability in temperature and precipitation over the Potwar Plateau is strongly influenced by large-scale atmospheric circulation patterns and regional topographic controls. The interaction between the South Asian summer monsoon and mid-latitude western disturbances governs seasonal and interannual precipitation variability, often leading to synchronized rainfall anomalies across stations [115]. In addition, broader climate drivers such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) play a significant role in modulating moisture transport and atmospheric instability over northern Pakistan. The relatively moderate warming observed in parts of the region, despite global warming trends, may be attributed to elevation effects,

land–atmosphere interactions, and localized cooling influences associated with soil moisture and vegetation feedbacks [84,116]. Furthermore, the complex topography of the Potwar Plateau modifies airflow patterns, enhances orographic precipitation in higher elevations such as Murree, and contributes to comparatively drier conditions in lowland areas such as Attock and Chakwal [84]. These combined circulation and topographic mechanisms provide a physical explanation for the spatial heterogeneity and temporal variability observed in the study, reinforcing the importance of considering regional climate drivers in interpreting long-term hydroclimatic trends.

The standardized precipitation anomaly (SPA) analysis provides additional insight into hydroclimatic variability by revealing shifts in drought patterns over time. While precipitation remained relatively stable between 1982 and 1990, a transition toward drier conditions is evident from 1990 to 2000, characterized by increased frequency and severity of drought events [117,118]. This trend continued into the 2000s, with predominantly negative SPA values, and intensified further after 2010, culminating in a significant precipitation deficit in 2022. Notably, despite the increasing precipitation trend observed in Attock, other stations remain vulnerable to drought conditions, indicating pronounced spatial heterogeneity in hydrological responses across the region [119,120]. Taken together, the combined temperature and precipitation analyses indicate that the Potwar Plateau is characterized by a stable thermal regime but a highly variable and evolving precipitation system. While temperature trends remain weak and statistically insignificant, precipitation patterns show signs of increasing variability and localized intensification, particularly in the post-2015 period and during extreme events such as the 2021 peak [121,122]. This apparent divergence suggests that climatic changes in the region are not expressed through gradual shifts in mean temperature but rather through increased variability and extremity in precipitation.

Collectively, the climate of the Potwar Plateau appears to be transitioning toward a more variable hydroclimatic regime, where strong interannual fluctuations, localized extremes, and increasing drought frequency coexist. Such conditions reflect the combined influence of monsoonal variability, topographic controls, and broader atmospheric processes, which together shape the region's complex climate dynamics. These findings highlight the limitations of relying solely on linear trend analysis to interpret climatic changes and emphasize the importance of incorporating variability and extreme-event analysis to better understand emerging patterns. From a practical perspective, the increasing variability in precipitation, coupled with stable temperature conditions, has important implications for water resource management, agriculture, and disaster risk reduction. The coexistence of extreme rainfall events and recurrent droughts increases the likelihood of both flooding and water scarcity, particularly in topographically sensitive areas such as Murree and Chakwal. Therefore, strengthening climate monitoring systems, improving hydrological modeling, and developing targeted adaptation strategies are essential to address the growing hydroclimatic uncertainty in the Potwar Plateau. Given the observed shifts in temperature and precipitation, future research should extend climate analyses beyond 2022 to better capture long-term variability and emerging trends. Integrating hydrological modeling will be essential for developing climate-resilient agricultural and water management strategies in the region. Additionally, further studies should incorporate socioeconomic and ecological dimensions, including vulnerability assessments and ecosystem responses to climate variability. Comparative analyses combined with local knowledge can enhance adaptive strategies and support sustainable development planning aligned with regional and global climate goals.

### *5.1. Limitations of the study*

This study is limited by the use of only six meteorological stations, which may not fully capture the spatial heterogeneity and micro-climatic variability of the Potwar Plateau. The station-based approach may overlook localized extremes occurring between observation points. In addition, the absence of population density and socio-economic data restricts a more comprehensive assessment of climate impacts on human and environmental systems. Despite these limitations, the dataset provides a reliable basis for evaluating long-term hydroclimatic trends in the region.

## 6. Conclusions

This study presents a comprehensive assessment of temperature and precipitation variability across the Potwar Plateau over the period 1982–2022, highlighting significant spatial and temporal heterogeneity driven by topographic controls and monsoonal influences. Temperature patterns exhibit a clear elevation-dependent gradient, with higher mean values observed at low-altitude stations such as Jhelum (35.2 °C in June) and comparatively lower values at elevated locations like Murree (30.09 °C). Similarly, minimum temperatures range from 12.47 °C at Jhelum to 8.21 °C at Murree, while Chakwal records the lowest value (5.57 °C), emphasizing the role of altitude in regulating thermal conditions. Despite these distinct spatial patterns, long-term temperature trends remain weak and statistically insignificant. Sen's slope estimates indicate slight declines at several stations, and low coefficients of determination ($R^2 < 0.05$) confirm that temperature variability is primarily driven by interannual fluctuations rather than sustained warming or cooling, indicating relative thermal stability over the study period. In contrast, precipitation demonstrates substantially greater variability, both seasonally and interannually, reflecting the dominant influence of the southwest monsoon and localized topographic effects. July consistently represents the peak rainfall month across all stations, with values reaching 204.74 mm at Jhelum and exceeding 200 mm at Islamabad and Rawalpindi, while Murree records 185 mm. However, pronounced intra-month variability is evident, with minimum values as low as 10.26 mm in Chakwal and 11.37 mm in Jhelum, highlighting the erratic nature of monsoonal rainfall. Annual precipitation varies widely, ranging from approximately 200 to 3300 mm, with mean values between 697 and 917.62 mm across stations, indicating strong interannual variability. Trend analysis reveals spatially heterogeneous precipitation changes. Attock is the only station exhibiting a statistically significant increasing trend ($\beta = 15.688$ mm/year, $p = 0.003$, $R^2 = 0.27$), while other stations show positive but nonsignificant trends, suggesting gradual but uneven intensification. The synchronized peak in 2021 further indicates recent monsoonal intensification driven by large-scale atmospheric processes. Additionally, standardized precipitation anomaly analysis reveals increasing drought frequency after 2000, intensifying after 2010, and culminating in a severe deficit in 2022. Overall, the findings indicate that while temperature remains relatively stable, precipitation patterns are becoming increasingly variable and extreme. This shift toward heightened hydroclimatic variability underscores growing environmental uncertainty and highlights the need for improved climate monitoring and adaptive water resource management strategies in the Potwar Plateau.

## 7. Practical implications

1. This research highlights the plateau's drought vulnerability, emphasizing the need for adaptive water management, including water conservation, reservoir improvements, and rainwater harvesting.

2. High monsoon precipitation in low-lying areas like Jhelum and Islamabad calls for targeted flood mitigation measures such as early warning systems, flood barriers, and improved drainage.

3. Documented shifts in precipitation and drought patterns underscore the need for climate-smart agriculture, including crop rotation, drought-resistant crops, and soil conservation.

4. The study provides climate data essential for developing adaptive policies, aiding local governments in formulating climate action plans, and achieving sustainable development goals.

## 8. Policy recommendations

1. Regional climate adaptation plans must address the Potwar Plateau's variable temperatures and rainfall to tackle water shortages and agricultural challenges effectively.

2. Pakistan should prioritize renewable energy, as shifting climate patterns may affect hydroelectricity on the Potwar Plateau, making solar, wind, and diversified hydropower investments crucial.

3. Climate-resilient agricultural policies are needed to counter droughts and irregular rainfall, focusing on crop diversification, soil management, and drought-resistant crops.

4. Rising flood risks in Islamabad, Attock, and Jhelum necessitate flood barriers, improved drainage, and early warning systems to protect communities.

## Author contributions

A.R. is responsible for drafting the principal manuscript, conceptualizing the methodology, conducting investigations, and curating the data. M.A. analyzed and interpreted the results. W.Q did the supervision and contributed to the refinement of the final manuscript. All authors have reviewed and approved the final version of the manuscript.

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## Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

## Conflict of interest

The authors declare no conflict of interest.

## References


1. Adnan RM, Liang ZM, Trajković S, et al. (2019) Daily streamflow prediction using optimally pruned extreme learning machine. *J Hydrol* 577: 123981. https://doi.org/10.1016/j.jhydrol.2019.123981
2. Guballa JD, Bollmann J, Akrami M, et al. (2024) Coccolithophore assemblage response to Indian Monsoon–ENSO teleconnections during the last century. *Paleoceanogr Paleoclimatol* 39: e2024PA004911. https://doi.org/10.1029/2024PA004911
3. Wang H, Su W (2013) Evaluating and understanding top of the atmosphere cloud radiative effects in Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) Coupled Model Intercomparison Project Phase 5 (CMIP5) models using satellite observations. *J Geophys Res: Atmos* 118: 683–699. https://doi.org/10.1029/2012JD018619
4. Ly M, Traore SB, Alhassane A, et al. (2013) Evolution of some observed climate extremes in the West African Sahel. *Weather Clim Extrem* 1: 19–25. https://doi.org/10.1016/j.wace.2013.07.005
5. Rawat A, Kumar D, Khati BS (2024) A review on climate change impacts, models, and its consequences on different sectors: a systematic approach. *J Water Clim Change* 15: 104–126. https://doi.org/10.2166/wcc.2023.536
6. De Luis M, Gonzalez-Hidalgo JC, Brunetti M, et al. (2011) Longares, Precipitation concentration changes in Spain 1946–2005. *Nat Hazards Earth Syst Sci* 11: 1259–1265. https://doi.org/10.5194/nhess-11-1259-2011
7. Yasin A, Shaheen R, Hasan M, et al. (2023) Case Study Analysis of Educational Policies, Resource Distribution, and Prevailing Inequities in Pakistan. *J Hum Dyn* 1: 23–30.
8. Rosenzweig BR, McPhillips L, Chang H, et al. (2018) Pluvial flood risk and opportunities for resilience. *WIREs Water* 5: e1302. https://doi.org/10.1002/wat2.1302
9. Materia S, García LP, van Straaten C, et al. (2024) Artificial intelligence for climate prediction of extremes: State of the art, challenges, and future perspectives. *WIREs Climate Change* 15: e914. https://doi.org/10.1002/wcc.914
10. Zhang Z, Zhang L, Liu Y, et al. (2024) Responses of annual streamflow variability to annual precipitation, extreme climate events and large-scale climate phenomena in the Qinghai-Tibet Plateau. *J Hydrol* 632: 130969. https://doi.org/10.1016/j.jhydrol.2024.130969
11. Saad S, Mahsud MI, Mian G (2024) Climate change impacts: exploring the rising climate-security nexus in Pakistan. *Lib Arts Soc Sci Int J* 8: 177–190. https://doi.org/10.47264/idea.lassij/8.1.10
12. Hussain W, Khan MA (2024) Climate change-induced glacial lake outburst floods in Hunza valley of Pakistan: An assessment of indigenous farming community perceptions and adaptation. *Environ Dev Sustain* 26: 11515–11539. https://doi.org/10.1007/s10668-023-03396-6
13. Kirsch TD, Wadhwani C, Sauer L, et al. (2012) Impact of the 2010 Pakistan floods on rural and urban populations at six months. *PLoS Curr* 4: e4fdfb212d2432. https://doi.org/10.1371/4fdfb212d2432

14. Saddique N, Khaliq A, Bernhofer C (2020) Trends in temperature and precipitation extremes in historical (1961–1990) and projected (2061–2090) periods in a data scarce mountain basin, northern Pakistan. *Stoch Environ Res Risk Assess* 34: 1441–1455. https://doi.org/10.1007/s00477-020-01829-6
15. Eckstein MK, Master SL, Xia L, et al. (2022) The interpretation of computational model parameters depends on the context. *Elife* 11: e75474. https://doi.org/10.7554/eLife.75474
16. Abbas M, Khan F, Liou Y, et al. (2024) Assessment of the impacts of climate change on the construction of homogeneous climatic regions and ensemble climate projections using CMIP6 data over Pakistan. *Atmos Res* 304: 107359. https://doi.org/10.1016/j.atmosres.2024.107359
17. Muzammal H, Zaman M, Safdar M, et al. (2024) Climate Change Impacts on Water Resources and Implications for Agricultural Management, In: Kanga S, Singh SK, Shevkani K, et al. Eds., *Transforming Agricultural Management for a Sustainable Future*, World Sustainability Series. Springer, Cham. https://doi.org/10.1007/978-3-031-63430-7_2
18. Janjua AA, Aslam M (2024) Climate-induced optimal wheat cropping season and mapping districts vulnerabilities in Punjab, Pakistan. *Environ Dev Sustain* 26: 5935–5958. https://doi.org/10.1007/s10668-023-02945-3
19. Fleiss M, Kienberger S, Aubrecht C, et al. (2011) Mapping the 2010 Pakistan floods and its impact on human life: A post-disaster assessment of socioeconomic indicators. *Geoinf Disaster Manag*.
20. Mahmood S, Rahman A, Sajjad A (2019) Assessment of 2010 flood disaster causes and damages in district Muzaffargarh, Central Indus Basin, Pakistan. *Environ Earth Sci* 78: 63. https://doi.org/10.1007/s12665-019-8084-8
21. Jonkman SN, Curran A, Bouwer LM (2024) Floods have become less deadly: an analysis of global flood fatalities 1975–2022. *Nat Hazards* 120: 6327–6342. https://doi.org/10.1007/s11069-024-06444-0
22. Ahmad Z, Hafeez M, Ahmad I (2012) Hydrology of mountainous areas in the upper Indus Basin, Northern Pakistan with the perspective of climate change. *Environ Monit Assess* 184: 5255–5274. https://doi.org/10.1007/s10661-011-2337-7
23. Tschumi E, Zscheischler J (2020) Countrywide climate features during recorded climate-related disasters. *Clim Change* 158: 593–609. https://doi.org/10.1007/s10584-019-02556-w
24. Shakoor MB, Bibi I, Niazi NK, et al. (2018) The evaluation of arsenic contamination potential, speciation and hydrogeochemical behaviour in aquifers of Punjab, Pakistan. *Chemosphere* 199: 737–746. https://doi.org/10.1016/j.chemosphere.2018.02.002
25. Hafeez S, Aftab R, Mirza B (2024) Assessing the impact of climate-driven water stress on agriculture growth of Pakistan. *J Humanit Soc Manag Sci* 5: 36–66. https://doi.org/10.47264/idea.jhsms/5.1.3
26. Warwick PD, Wardlaw BR (2007) *Regional studies of the Potwar plateau area, northern Pakistan*, US Department of the Interior, US Geological Survey.
27. Safdar F, Khokhar MF, Mahmood F, et al. (2023) Observed and predicted precipitation variability across Pakistan with special focus on winter and pre-monsoon precipitation. *Environ Sci Pollut Res* 30: 4510–4530. https://doi.org/10.1007/s11356-022-22502-1
28. Hafeez A, Dangel W, Ostroff S, et al. (2023) The state of health in Pakistan and its provinces and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *Lancet Glob Health* 11: e229–e243.

29. Zaman M, Shahid MA, Ahmad I, et al. (2023) Spatiotemporal variability of precipitation concentration in Pakistan. *Int J Climatol* 43: 7646–7666.
30. Niaz R, Almazah MMA, Hussain I, et al. (2022) Assessing the probability of drought severity in a homogeneous region. *Complexity* 2022: 3139870. https://doi.org/10.1155/2022/3139870
31. Batool S, Mahmood SA, Shirazi SA (2024) Drought Assessment in Potwar Region, Punjab Pakistan During 1981–2019, *The Water, Climate, and Food Nexus,* Springer, Cham, 265–280. https://doi.org/10.1007/978-3-031-50962-9_12
32. Wang S, Abbas J, Sialet MS, et al. (2022) Achieving green innovation and sustainable development goals through green knowledge management: Moderating role of organizational green culture. *J Innov Knowl* 7: 100272. https://doi.org/10.1016/j.jik.2022.100272
33. Khan AG (2001) Relationships between chromium biomagnification ratio, accumulation factor, and mycorrhizae in plants growing on tannery effluent-polluted soil. *Environ Int* 26: 417–423. https://doi.org/10.1016/S0160-4120(01)00022-8
34. Khan IA, Bridge JS, Kappelman J, et al. (1997) Evolution of Miocene fluvial environments, eastern Potwar plateau, northern Pakistan. *Sedimentology* 44: 221–251. https://doi.org/10.1111/j.1365-3091.1997.tb01522.x
35. Shaji AM, Haripriya H, Anusha CR, et al. (2024) Spatio-temporal analysis of meteorological variables over India for 21st century approach with CMIP6 climate models.
36. Ansari R, Grossi G (2022) Performance evaluation of raw and bias-corrected ERA5 precipitation data with respect to extreme precipitation analysis: case study in Upper Jhelum Basin, South Asia. *Theor Appl Climatol* 150: 1409–1424. https://doi.org/10.1007/s00704-022-04239-6
37. Hanadé Houmma I, El Mansouri L, Gadal S, et al. (2022) Modelling agricultural drought: a review of latest advances in big data technologies. *Geomat Nat Hazards Risk* 13: 2737–2776. https://doi.org/10.1080/19475705.2022.2131471
38. Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. *J Am Stat Assoc* 63: 1379–1389. https://doi.org/10.1080/01621459.1968.10480934
39. Yue S, Wang CY (2002) Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test. *Water Resour Res* 38: 4-1–4-7. https://doi.org/10.1029/2001WR000861
40. Xu,Y, Si D, Cao L, et al. (2025) The changes in heating and cooling energy demand in Beijing and Shanghai under global warming. *J Appl Meteorol Climatol* 64: 413–424. https://doi.org/10.1175/JAMC-D-24-0039.1
41. Wang XL, Chen HF, Wu YH, et al. (2010) New techniques for the detection and adjustment of shifts in daily precipitation data series. *J Appl Meteorol Climatol* 49: 2416–2436. https://doi.org/10.1175/2010JAMC2376.1
42. Saha S, Kundu B, Paul GC, et al. (2023) Proposing an ensemble machine learning based drought vulnerability index using M5P, dagging, random sub-space and rotation forest models. *Stoch Environ Res Risk Assess* 37: 2513–2540. https://doi.org/10.1007/s00477-023-02403-6
43. Pebesma EJ (2004) Multivariable geostatistics in S: the gstat package. *Comput Geosci* 330: 683–691.
44. Tan WY, Lai SH, Teo FY, et al. (2022) State-of-the-Art Development of Two-Waves Artificial Intelligence Modeling Techniques for River Streamflow Forecasting. *Arch Computat Methods Eng* 29: 5185–5211. https://doi.org/10.1007/s11831-022-09763-2.

45. Abbas S, Waseem M, Yaseen M, et al. (2023) Spatial-temporal seasonal variability of extreme precipitation under warming climate in Pakistan. *Atmosphere* 14: 210. https://doi.org/10.3390/atmos14020210
46. Khan F, Ali S, Mayer C, et al. (2022) Climate change and spatio-temporal trend analysis of climate extremes in the homogeneous climatic zones of Pakistan during 1962–2019. *Plos One* 17: e0271626. https://doi.org/10.1371/journal.pone.0271626
47. Nabi S, Ahanger MA, Dar AQ (2023) Spatio-temporal variability of temperature and precipitation in a Himalayan watershed. *Nat Hazards* 115: 1743–1760. https://doi.org/10.1007/s11069-022-05616-0
48. Rebi A, Hussain A, Hussain I, et al. (2023) Spatiotemporal precipitation trends and associated large-scale teleconnections in northern Pakistan. *Atmosphere* 14: 871. https://doi.org/10.3390/atmos14050871
49. Batool H, Taqui M (2024) Evaluating climate change for the early 21st century in the Potwar Region of Pakistan using CMIP6 simulations. *Earth Sci Inform* 17: 2213–2231. https://doi.org/10.1007/s12145-024-01277-8
50. Rasool G, Anjum MN, Anjum DY, et al. (2024) Projecting climate change impact on precipitation patterns during different growth stages of rainfed wheat crop in the Pothwar Plateau, Pakistan. *Climate* 12: 110. https://doi.org/10.3390/cli12080110
51. Wang Z, Xu X, Waili Y, et al. (2023) The Impacts of Climate Change on Vegetation Productivity and the Trends of the Impacts in Pakistan over the Last Two Decades.
52. Haider S, Rashid M, Tariq AUR, et al. (2025) Seasonal variability in hydrologic responses due to climate and land-cover changes in the Pothohar plateau, Pakistan. *J Water Clim Change* 16: 2407–2428. https://doi.org/10.2166/wcc.2025.527
53. Sohail A, Lee S (2024) Changes of Extreme Precipitation Trends in Pakistan during. 1–24.
54. Dimri A, Palazzi E, Daloz AS (2022) Elevation dependent precipitation and temperature changes over Indian Himalayan region. *Clim Dyn* 59: 1–21. https://doi.org/10.1007/s00382-021-06113-z
55. Kumar P, Sharma K (2023) *Snowfall shift and precipitation variability over sikkim himalaya attributed to elevation-dependent warming. J Atmos Sci Res* 6.
56. Choudhary A, Mahato S, Roy PS, et al. (2023) Analyzing the long-term variability and trend of aridity in India using non-parametric approach. *Stoch Environ Res Risk Assess* 37: 3837–3854. https://doi.org/10.1007/s00477-023-02483-4
57. Ashraf MS, Tariq MAUR (2025) Non-Monotonic Spatiotemporal Variability of Hydro-meteorological Variables Over Upper Indus Basin, Northern Pakistan. *North Pak.* http://dx.doi.org/10.2139/ssrn.5741410
58. Adnan S, Ullah K (2022) Long-term trends in climate parameters and multiple indices for drought monitoring over Pakistan. *Meteorol Atmos Phys* 134: 75. https://doi.org/10.1007/s00703-022-00908-3
59. Rashid A, Xinyu Z, Wang QX (2026) Investigating the Spatiotemporal Dynamics of Temperature and Precipitation Extremes Across the Loess Plateau Region in China During 1982–2023. *Int J Climatol* 46: e70177.
60. Gul S, Ren J (2022) Application of non-parametric innovative trend analysis of different time scale precipitation during (1951–2016) in Khyber Pakhtunkhwa, Pakistan. *Acta Geophys* 70: 485–503. https://doi.org/10.1007/s11600-021-00703-5

61. Haider S, Haq F, Kontakiotis G, et al. (2025) Spatiotemporal analysis of temperature variability and trends in the cholistan desert, Pakistan: Implications for water management and sustainable development. *Environ Earth Sci* 84: 665. https://doi.org/10.1007/s12665-025-12665-8
62. Sheraz K, Khan TA (2022) Spectral analysis of temperature and rainfall trends using hybrid nonparametric-wavelet transform method. *Sarh J Agric* 38: 1105–1123. https://dx.doi.org/10.17582/journal.sja/2022/38.3.1105.1123
63. Mohammad L, Mondal I, Bandyopadhyay J, et al. (2022) Assessment of spatio-temporal trends of satellite-based aerosol optical depth using Mann–Kendall test and Sen's slope estimator model. *Geomat Nat Hazards Risk* 13: 1270–1298.
64. Kumar A, Attri PK (2024) Analysis of Pre-monsoon and Post-monsoon Seasonal Rainfall Trends by Mann-Kendall and Sen's Slope Estimator Test in Himachal Pradesh, India. *Curr World Environ* 19: 998–1010. https://dx.doi.org/10.12944/CWE.19.2.37
65. Iyeme E, Ekah UJ, Njok AO, et al. (2024) Trend Analysis of Climate Change across Nigeria: A Mann-Kendall and Sen's Approach. *Arch Curr Res Int* 24: 450–467.
66. Whipple K, Adams B, Forte A, et al. (2023) Eroding the Himalaya: Topographic and climatic control of erosion rates and implications for tectonics. *J Geol* 131: 265–288. https://doi.org/10.1086/731260
67. Abdulfattah IS, Rajab JM, Chaabane M, et al. (2025) Trend analysis of air surface temperature using Mann-Kendall test and Sen's slope estimator in Tunisia. *J Agrometeorol* 27: 355–359. https://doi.org/10.54386/jam.v27i3.3003
68. Ahmed K, Shahid S, Wang X, et al. (2019) Spatiotemporal changes in aridity of Pakistan during 1901–2016. *Hydrol Earth Syst Sci* 23: 3081–3096.
69. Farooq I, Shah AR, Salik KM, et al. (2021) Annual, seasonal and monthly trend analysis of temperature in Kazakhstan during 1970–2017 using non-parametric statistical methods and GIS technologies. *Earth Syst Environ* 5: 575–595. https://doi.org/10.1007/s41748-021-00244-3
70. Asgher S, Ahmad M, Kumar N, et al. (2021) Trend analysis of temperature and rainfall using Mann Kendall test and Sen's slope estimator in Bhaderwah Tehsil of Doda District. *Res J Agric Sci* 12: 1021–1026.
71. Liaqat MU, Grossi G, Hasson S, et al. (2022) Characterization of interannual and seasonal variability of hydro-climatic trends in the Upper Indus Basin: Characterization of interannual and seasonal variability of hydro-climatic trends in the Upper Indus Basin. *Theor Appl Climatol* 147: 1163–1184. https://doi.org/10.1007/s00704-021-03850-3
72. Akhtar IuH, Athar H (2019) Contribution of changing precipitation and climatic oscillations in explaining variability of water extents of large reservoirs in Pakistan. *Sci Rep* 9: 19022. https://doi.org/10.1038/s41598-019-54872-x
73. Bhatti AS, Wang G, Ullah W, et al. (2020) Trend in extreme precipitation indices based on long term in situ precipitation records over Pakistan. *Water* 12: 797. https://doi.org/10.3390/w12030797
74. Ali N, Ahmad I, Chaudhry A, et al. (2015) Trend analysis of precipitation data in Pakistan. *Sci Int* 27: 803–808.
75. Dawood M, Rahman Au, Rahman G, et al. (2024) Geo-statistical analysis of climatic variability and trend detection in the Hindu Kush region, North Pakistan. *Environ Monit Assess* 196: 4. https://doi.org/10.1007/s10661-023-12175-9

76. Kumar A, Scaife AA, Merryfield WJ, et al. (2024) World meteorological organization (WMO)-accredited infrastructure to support operational climate prediction. *Bull Am Meteorol Soc* 105: E2126–E2143. https://doi.org/10.1175/BAMS-D-23-0284.1
77. Kennedy J, Trewin B, Betts R, et al. (2024) *State of the Climate 2024. Update for COP29*, World Meteorological Organization.
78. Hoyos CD, Webster PJ (2007) The role of intraseasonal variability in the nature of Asian monsoon precipitation. *J Clim* 20: 4402–4424. https://doi.org/10.1175/JCLI4252.1
79. Latif M, Syed F, Hannachi A (2017) Rainfall trends in the South Asian summer monsoon and its related large-scale dynamics with focus over Pakistan. *Clim Dyn* 48: 3565–3581. https://doi.org/10.1007/s00382-016-3284-3
80. Ashfaq M, Johnson N, Kucharski F, et al. (2023) The influence of natural variability on extreme monsoons in Pakistan. *npj Clim Atmos Sci* 6: 148. https://doi.org/10.1038/s41612-023-00462-8
81. Ullah W, Karim A, Ullah S, et al. (2023) An increasing trend in daily monsoon precipitation extreme indices over Pakistan and its relationship with atmospheric circulations. *Front Environ Sci* 11: 1228817.
82. Rashid A, Wang QX (2025) Integrating disaster, catastrophe, and climate change education in Pakistan's educational curriculum and state institutions: A comprehensive review. *Clim Res* 94: 1–18. https://doi.org/10.3354/cr01747
83. Wang J, Yan R, Wang J, et al. (2025) The content, chemical forms, and ecological environmental risks of trace elements in coal ash. J Environ Chem Eng 133: 117772. https://doi.org/10.1016/j.jece.2025.117772.
84. Xie J, Hsu PC, Lee JY, et al. (2024) Tropical intraseasonal oscillations as key driver and source of predictability for the 2022 Pakistan record-breaking rainfall event. *npj Clim Atmos Sci* 7: 256. https://doi.org/10.1038/s41612-024-00809-9
85. Adnan M, Firdos K, Nadia R, et al. (2021) Variability and predictability of summer monsoon rainfall over Pakistan. *Asia-Pac J Atmos Sci* 57: 89–97. https://doi.org/10.1007/s13143-020-00178-2
86. Mehmood M, Hassan M, Iqbal W, et al. (2022) Spatiotemporal variation in temperature extremes and their association with large scale circulation patterns in the Central Karakorum during 1982–2019. *Atmos Res* 267: 105925. https://doi.org/10.1016/j.atmosres.2021.105925
87. Chen G, Ling G, Lin Z, et al. (2023) Role of tropical-extratropical interactions in the unprecedented 2022 extreme rainfall in Pakistan: a historical perspective. *Atmos Res* 291: 106817. https://doi.org/10.1016/j.atmosres.2023.106817
88. Amin A, Nasim W, Mubeen M, et al. (2017) Comparison of future and base precipitation anomalies by SimCLIM statistical projection through ensemble approach in Pakistan. *Atmos Res* 194: 214–225. https://doi.org/10.1016/j.atmosres.2017.05.002
89. Baig S, Sayama T, Yamada M (2022) Quantifying the changes in the runoff and its components across the Upper Indus River Basin under climate change. *J Water Clim Change* 13: 3416–3434. https://doi.org/10.2166/wcc.2022.153
90. Latif Y, Yaoming M, Yaseen M (2018) Spatial analysis of precipitation time series over the Upper Indus Basin. *Theor Appl Climatol* 131: 761–775.
91. Ali SHB, Shafqat MN, Eqani SAMAS, et al. (2019) Trends of climate change in the upper Indus basin region, Pakistan: implications for cryosphere. *Environ Monit Assess* 191: 51. https://doi.org/10.1007/s10661-018-7184-3

92. Hussain A, Cao J, Hussain I, et al. (2021) Observed trends and variability of temperature and precipitation and their global teleconnections in the Upper Indus Basin, Hindukush-Karakoram-Himalaya. *Atmosphere* 12: 973. https://doi.org/10.3390/atmos12080973
93. Rizwan M, Li X, Jamal K, et al. (2019) Precipitation variations under a changing climate from 1961–2015 in the source region of the Indus River. *Water* 11: 1366. https://doi.org/10.3390/w11071366
94. Xie H, Ringler C, Zhu T, et al. (2013) Droughts in Pakistan: a spatiotemporal variability analysis using the Standardized Precipitation Index. *Water Int* 38: 620–631. https://doi.org/10.1080/02508060.2013.827889
95. Trenberth KE (2005) The impact of climate change and variability on heavy precipitation, floods, and droughts. *Encycl Hydrol Sci* 17: 1–11.
96. Sun Q, Zhang X, Zwiers F, et al. (2021) A global, continental, and regional analysis of changes in extreme precipitation. *J Clim* 34: 243–258. https://doi.org/10.1175/JCLI-D-19-0892.1
97. Archer DR, Fowler HJ (2004) Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications. *Hydrol Earth Syst Sci* 8: 47–61.
98. Khan I, Waqas T, Samiullah, et al. (2020) Precipitation variability and its trend detection for monitoring of drought hazard in northern mountainous region of Pakistan. *Arab J Geosci* 13: 698. https://doi.org/10.1007/s12517-020-05700-4
99. Jamshadali V, Reji M, Varikoden H, eet al. (2021) Spatial variability of south Asian summer monsoon extreme rainfall events and their association with global climate indices. *J Atmos Sol-Terr Phys* 221: 105708.
100. Khan M, Munoz-Arriola F, Rehana S,et al. (2019) Spatial heterogeneity of temporal shifts in extreme precipitation across India. *J Clim Change* 5: 19–31. https://doi.org/10.3233/JCC190003
101. Huang Y, Zhang F, Wang Z, et al. (2025) Millennial-scale precipitation isotope variability reveals spatial heterogeneity in Asian monsoon moisture during the last glacial period. *Glob Planet Change*, 105228. https://doi.org/10.1016/j.gloplacha.2025.105228
102. Altmanova N, Fibich P, Doležal J, et al. (2025) Spatial heterogeneity of tree-growth responses to climate across temperate forests in Northeast Asia. *Agric For Meteorol* 362: 110355. https://doi.org/10.1016/j.agrformet.2024.110355
103. He B, Gao F, Wu B, et al. (2025) Incorporating spatial heterogeneity into the analysis of snow cover variability and drivers in the High Mountain Asia region. *J Hydrol* 2025: 134080. https://doi.org/10.1016/j.jhydrol.2025.134080
104. Hultgren A, Carleton T, Delgado M, et al. (2025) *Impacts of climate change on global agriculture accounting for adaptation.* Nature 642: 644–652. https://doi.org/10.1038/s41586-025-09085-w
105. Forster PM, Smith C, Walsh T, et al. (2024) Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence. *Earth Syst Sci Data* 16: 2625–2658. https://doi.org/10.5194/essd-16-2625-2024
106. Meyer P, Jouanne F, Doin MP, et al. (2024) Present-day quantification of seismic coupling along the décollement level beneath the Potwar Plateau region in Pakistan western Himalaya. *Earth Planet Sci Lett* 637: 118723. https://doi.org/10.1016/j.epsl.2024.118723
107. Ashraf A, Ali M (2025) Appraisal of spring distribution across rain-fed plateau of Pakistan for sustainable development. *Discov Water* 5: 46. https://doi.org/10.1007/s43832-025-00242-w
108. Ahmed K, Shahid S, Chung ES, et al. (2017) Spatial distribution of secular trends in annual and seasonal precipitation over Pakistan. *Clim Res* 74: 95–107. https://doi.org/10.3354/cr01489

109. Iqbal SW, Latif M, Ahmed R, et al. (2022) Performance evaluation and comparison of observed and reanalysis gridded precipitation datasets over Pakistan. *Theor Appl Climatol* 149: 1093–1116. https://doi.org/10.1007/s00704-022-04100-w
110. Ahmad K, Banerjee A, Rashid W, et al. (2022) Assessment of long-term rainfall variability and trends using observed and satellite data in central Punjab, Pakistan. *Atmosphere* 14: 60. https://doi.org/10.3390/atmos14010060
111. Hussain A, Cao J, Ali S, et al. (2022) Observed trends and variability of seasonal and annual precipitation in Pakistan during 1960–2016. *Int J Climatol* 42: 8313–8332.
112. Rahman KU, Shang S, Shahid M, et al. (2020) Hydrological evaluation of merged satellite precipitation datasets for streamflow simulation using SWAT: a case study of Potohar Plateau, Pakistan. *J Hydrol* 587: 125040. https://doi.org/10.3390/10.1016/j.jhydrol.2020.125040
113. Latif M, Shireen H, Adnan S, et al. (2024) Drought variability in Pakistan: Navigating historical patterns in a changing climate with global teleconnections. *Theor Appl Climatol* 155: 8379–8400. https://doi.org/10.1007/s00704-024-05138-8
114. Shahid M, Rahman KU (2021) Identifying the annual and seasonal trends of hydrological and climatic variables in the Indus Basin Pakistan. *Asia-Pacific J Atmos Sci* 57: 191–205. https://doi.org/10.1007/s13143-020-00194-2
115. Doi T, Behera SK, Yamagata T (2024) Seasonal predictability of the extreme Pakistani rainfall of 2022 possible contributions from the northern coastal Arabian Sea temperature. *npj Clim Atmos Sci* 7: 13. https://doi.org/10.1038/s41612-023-00557-2
116. Hunt KM, Baudouin JP, Turner AG, et al. (2025) Western disturbances and climate variability: a review of recent developments. *Weather Clim Dynam* 6: 43–112. https://doi.org/10.5194/wcd-6-43-2025
117. Raza I, Khalid P, Qureshi J, et al. (2022) Remote Sensing/GIS Application For groundwater prospecting in Potwar Plateau, Pakistan.
118. Ain N, Latif M, Ullah K, et al. (2020) Investigation of seasonal droughts and related large-scale atmospheric dynamics over the Potwar Plateau of Pakistan. *Theor Appl Climatol* 140: 69–89. https://doi.org/10.1007/s00704-019-03064-8
119. Khan MW, Ahmad S, Dahri ZH, et al. (2023) Development of high resolution daily gridded precipitation and temperature dataset for potohar plateau of indus basin. *Theor Appl Climatol* 154: 1179–1201. https://doi.org/10.1007/s00704-023-04626-7
120. Riaz K, Ahmad B, Bukhari SAA, et al. (2020) Estimating the impact of climate extremes and their future projections over drought prone regions of Punjab, Pakistan. *Clim Change* 6: 212–227.
121. Abbas A, Ullah S, Ullah W, et al. (2023) Characteristics of winter precipitation over Pakistan and possible causes during 1981–2018. *Water* 15: 2420. https://doi.org/10.3390/w15132420
122. Liu Q, Yao X, Huang Y (2025) Rainfall Events of Different Durations over the Tibetan Plateau in Boreal Summer as Revealed by the GPM Data. *J Clim* 38: 2623–2639. https://doi.org/10.1175/JCLI-D-23-0669.1




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