# Spatiotemporal Analysis of Drought and Rainfall in Pakistan via Standardized Precipitation Index: Homogeneous Regions, Trend, Wavelet and Influence of El Niño-Southern Oscillation

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# Spatiotemporal analysis of drought and rainfall in Pakistan via Standardized Precipitation Index: Homogeneous regions, trend, wavelet and influence of El Niño-Southern Oscillation

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## Abstract

The phenomena of drought is common in the world, particularly in Pakistan. Drought in Pakistan has been studied in terms of its spatial and temporal variability, as well as its impact on the El Niño-Southern Oscillation (ENSO) cycle. The objectives of this study are to identify homogeneous rainfall regions and their trend regions, as well as the impact of ENSO cycle. For the analysis, 44 meteorological sites during 1980-2019 are used for monthly rainfall data. The descriptive and exploratory statistics tests (e.g., Pettitt and Mann-Kendall—MK), Sen method, and cluster analysis (CA) are implemented with the annual Standardized Precipitation Index (SPI). The ENSO occurrences were classified based on the Oceanic Nio Index (ONI) for region 3.4. Using the Cophenetic Correlation Coefficient (CCC) and a significance level of 5%, seven approaches were applied to the pluviometric dataset. The CCC > 0.9082 indicates that the Complete approach is the best. According to the CA method, Pakistan has four homogenous rainfall groups (G1, G2, G3, and G4). Descriptive and exploratory statistics yielded lower values for G1 than for the other groups. Pettitt's technique identified the most extreme El Niño years in terms of the drought's spatial and temporal variability. According to the Pettitt test, the wettest months were March, August, September, June, and December. Non-significant increases in Pakistan's annual rainfall were found in the MK test, with exceptions in the southern and northern regions, respectively. No significant rise in Pakistan's rainfall was found using Sen's Sen's approach, especially in the G2, G3, and G4 regions. The severity of the drought in Pakistan is made worse by months, homogeneous groups of rainfall, and El Niño events, all of which require public officials' attention while managing water resources, agriculture, and the country's economy.



**Keywords**: drought index; climate variability; cluster analysis; ENSO; water resources.

## 1. Introduction

Drought is a natural phenomenon defined as water scarcity in a certain period of time, varies between months to year, or even several years (McKee *et al.* 1993; Gonçalves *et al.* 2021), being common across the world (WMO 2021). Numerous studies are based on quantifying the severity degree via drought indexes and different calculation methods prevailing in the literature, for example, the Palmer Drought Severity Index (PDSI), Rainfall Anomaly Index (RAI), Vegetation Condition Index (VCI), Soil Moisture Deficit Index (SMDI), Standardizerd Runoff Index (SRI), Single Z-Index, among others (Heim Jr. 2002; Oliveira Júnior *et al.* 2012; Beguería *et al.* 2014; Sobral *et al.* 2018; Fung *et al.* 2020; Costa *et al.* 2021; Gonçalves *et al.* 2021). These indices identify the duration, frequency and intensity of the drought (Kim *et al.*, 2014; Carmo and Lima 2020; Ho *et al.* 2021; Oliveira-Júnior *et al.* 2021). Furthermore, they use hydro-meteorlogical variables such as rainfall, evapotranspiration (ET), surface air temperature, soil moisture and runoff as input data (Mishra and Singh 2010; Zagar *et al.* 2011; Beguería *et al.* 2014; Sobral *et al.* 2018).

The Standardized Precipitation Index (SPI), which uses solely rain as an input, is the most often used index in the scientific literature for drought identification (McKee *et al.* 1993), which is a consensus among several experts (Mishra and Singh 2010; Zagar *et al.* 2011; Oliveira Júnior *et al.* 2012; Khan and Gadiwala 2013; Kim *et al.* 2014; Lyra *et al.* 2017; Terassi *et al.* 2020; Oliveira-Júnior *et al.*

2021). The World Meteorological Organization (WMO) - (WMO 2021) has recognized the SPI as a reliable tool for monitoring meteorological droughts.

Adnan *et al.* (2018) previously studied 15 drought indices in Pakistan and compared them using various statistical tests, concluding that the SPI, Standardized Precipitation Evapotranspiration Index (SPEI), and Reconnaissance Drought Index (RDI) had a solid capacity to monitor drought in the country. Throughout Pakistan, the severity and frequency of SPEI-based droughts increase during the main seasons (Rabbi and Kharif). Drought intensity increases in primarily dry and semi-arid regions for both growing seasons.

According to the findings by Ahmed *et al.* (2018),Droughts have been severe and recurrent in Pakistan, particularly in arid and semi-arid regions (Salma *et al.* 2012; Anjum *et al.* 2012), increasing the social vulnerability of the country's population (Ahmed *et al.* 2018; Adnan *et al.* 2018) by undermining the country's livelihood, agriculture, and economy (Hussain and Lee 2009; Hanif *et al.* 2013; Ullah *et al.* 2021). Ullah *et al.* (2021) have examined meteorological drought in multiscales (3, 6, and 12 months intervals) during a 35-year period using SPI and SPEI. Rather than using reanalysis products, the authors employed in situ data (Climatic Research Unit - CRU TS, National Centers for Environmental Prediction version II - NCEP-2, European Center for Medium-Range Weather Forecasts Version-5 - ERA-5, and Modern-Era Retrospective analysis for Research and Applications version II - MERRA-2). The findings revealed that the products (i.e., CRU TS and MERRA-2) could accurately identify drought in the country's south, except for overestimation in the east and west sectors (ERA-5 and NCEP-2). Hanif *et al.* (2013) investigated the processes and precursors of drought dynamics in Pakistan, finding that exceptional drought episodes in the Pacific and Indian oceans are significantly associated with wind patterns and the intrinsic weather system.

In Pakistan, several studies on drought assessment and monitoring have been conducted (e.g., Salma *et al.* 2012; Anjum *et al.* 2012; Adnan *et al.* 2018; Ullah *et al.* 2021). Few studies, however, have correlated with the phases of climate variability mode, such as ENSO – (Ahmad *et al.* 2010; Ahmad *et al.* 2014; Hina *et al.* 2021), followed by the definition of homogeneous rainfall regions (Hussain and Lee 2009) in the country and the best cluster analysis (CA) method, while still using a consistent time series observed (Anjum *et al.* 2012; Salma *et al.* 2012; Khan and Gadiwala 2013; Xie *et al.* 2013; ADB 2017). Therefore, motivated by the gaps that still exist with the meteorological trends and phenomena, the objectives of the study are: **i**) to assess spatiotemporality of the drought based on the annual SPI; **ii**) identify homogeneous regions and rainfall trends; and **iii**) influence of ENSO phases on the dynamics of drought in Pakistan.

## 2. Materials and Methods

### *2.1. Study area*

Pakistan is geographically situated between 24-37° N latitudes and 62-75° E longitudes in the western zone of south Asia (Salma *et al.* 2012). Pakistan has five Provinces namely, Punjab, Sind, Balochistan, Gilgit-Baltistan and Khyber

Pukhtunkhwa (KP) – (Hussain and Lee 2009). Furthermore, Pakistan is separated between tropical and subtropical zones, with 75 percent of the overall landmass (mostly in Pakistan's South) receiving less rainfall in the winter and experiencing high temperatures in the summer (Adnan 2016).

**Figure 1**

### *2.2 Rainfall data*

Monthly rainfall data from 44 meteorological stations were used in the study, as indicated in Table 1. With the exception of the Mangla station, which has a 21-year gap in the time series and was thus eliminated from the analyses, the data in time series is completely uniform.

**Table 1**

### *2.3 Pettitt and Mann-Kendall tests*

The current research used the Pettitt test to identify the years of possible abrupt changes in Pakistan's average rainfall time series (Pettitt 1979). The Pettitt test is a non-parametric test, which checks whether two samples $X_1$, $X_2$ ..., $X_t$ and $X_{t+1}$, $X_{t+2}$ ..., $X_T$ belong to the same population. The statistics of $k(t) = U_{t,T}$ performs a count of some times for a member of the 1st sample to be greater than the member of the 2nd sample. According to below Eq. (1):

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} \operatorname{sgn}(X_j - X_i) \qquad \textbf{(1)}$$

where, sgn is the coefficient given by the following conditions: sgn = +1 if ($X_j$ – $X_i$) > 0; sgn = 0 if ($X_j$ – $X_i$) = 0; sgn = –1 if ($X_j$ – $X_i$) < 0; $T$ is the size of time series; and $i$ and $j$ denote the time indices associated with individual values.

The statistics $U_{t,T}$ is then calculated for the values of $1 \leq t < T$, and so the $k(t)$ statistic of the test corresponds to the maximum in the absolute value of $U_{t,T}$ and, thus, the years where the abrupt change occurs are estimated, given by Eq. (2):

$$k(t) = \underset{1 \leq t < T}{\mathrm{Max}} \left|U_{t,T}\right| \quad \textbf{(2)}$$

The Pettitt test locates the point where there is an abrupt change in the mean of a time series, and its significance is given by Eq. (3):

$$p \cong 2\exp\left[\frac{-6k(t)^2}{\left(T^3+T^2\right)}\right] \quad \textbf{(3)}$$

The sudden change point is $t$, where the maximum of $k(t)$ occurred, then the critical values of $k$ ($k_{crit}$) are calculated by Eq. (4):

$$k_{\mathrm{crit}} = \pm\sqrt{\frac{\ln\left(\frac{p}{2}\right)\left(T^3+T^2\right)}{6}} \quad \textbf{(4)}$$

The Mann-Kendall (MK) test – (Mann 1945; Kendall 1975) was applied to Pakistan's rainfall time series, where $x_i$ is of n terms ($1\leq i \leq n$) and the MK test statistic is set to $x = x_1, x_i, x_j..., x_n$ according to Eq. (5). This test is also known as a distribution-free (non-parametric) test.

$$S = \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \quad \textbf{(5)}$$

where, $x_i$ is the estimated data of the sequence of values, $n$ is the length of the time series, and sgn = 1 for ($x_j$ - $x_i$)>0; sgn = 0 for ($x_j$ - $x_i$)=0; sgn = -1 for ($x_j$ - $x_i$)<0.

For time series $x_1$, $x_2$, $x_3$..., $x_n$ with a high number of terms (n>4) under the null hypothesis ($H_0$) of an absence of a trend, $S$ will present a normal distribution with mean and variance, where the variance of $S$ is denoted by $Var(S)$ from Eq. (6):

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \tag{6}$$

In this way, with the data repetitions, the variance is given by Eq. (7):

$$Var(S) = \frac{1}{18}\left[ n(n-1)(2n+5) - \sum_{p=1}^{g} t_p (t_p - 1)\,(2t_p + 5) \right] \tag{7}$$

where $n$ is the number of observations; $t_p$ is the number of observations with equal values in a specific $p_{th}$ group, and $g$ is the number of groups containing equal values in the data series in a particular $p_{th}$ group. The second term represents an adjustment for censored data.

By testing the statistical significance of $S$ for $H_0$ based on a two-tailed test, which in turn can be rejected for high values of the $Z$ statistic given by Eq. (8):

$$Z_{MK} = \left\{ \begin{array}{c} \frac{S-1}{\sqrt{Var(S)}}\ for\ S > 0 \\ 0\ for\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}\ for\ S < 0 \end{array} \right\} \tag{8}$$

Based on the $Z_{MK}$ statistic (Table 2), the decision is made to accept or reject $H_0$ that is, $H_0$ is accepted when the time series has no trend and rejected in favour of the alternative hypothesis ($H_1$) when there is a trend in the time series, in short:

$H_0$: There is no statistically significant trend in the time series; that is, the trend is statistically insignificant for p-value>$\alpha$;

$H_1$: There is a statistically significant trend in the time series for p-value>$\alpha$.

**Table 2**

For the analysis of the results in Pakistan, the Z-statistic values via the SPI-12 map are used. Positive values ($Z > 0$) show an increasing trend, while negative values ($Z < 0$) show a decreasing trend. The significance level ($\alpha$) adopted in the study was $\alpha = 0.05$ for the MK and Pettitt tests. If the probability $p$ of the MK test is less than the level $\alpha$, $p < \alpha$, there is a significant trend, while a value of $p > \alpha$, an insignificant trend. When there is no trend, the value of $Z$ is close to 0, and the value of $p$ is close to $\alpha$.

### *2.4. Standardized Precipitation Index - SPI*

The SPI formulation is based on the density and Gamma probability function (Eq. (5)) that is calculated every month, where $\alpha$ is the shape parameter ($\alpha > 0$), $\beta$ is the scale parameter ($\beta$>0) which is determined using the maximum likelihood method; $x$ is the amount of rainfall that can vary according to $\alpha$ and $\beta$.

The assigned values are normalized and transformed to a normal distribution (i.e., mean zero and variance one) - (McKee *et al.* 1993; Oliveira Júnior *et al.* 2012). The SPI calculation uses only rainfall values (Lyra *et al.* 2017; Carmo and Lima 2020) and categorizes a drought event either when the SPI presents continuous negative values or when the SPI is positive, and the drought event ends (McKee *et al.* 1993; Oliveira Júnior *et al.* 2012). Further details on the mathematical formulations and the statistical procedures used in calculating the SPI can be found in McKee *et al.* (1993).

$$g(x)= \frac{1}{\beta^{\alpha}\Gamma(\alpha)}\, x^{\alpha-1}\, e^{-\frac{x}{\beta}} \quad \textbf{(9)}$$

where $\Gamma(\alpha)$ is the gamma function.

After the calculation, the SPI was categorized according to Table 3 and analyzed on the annual scale (SPI-12). For the analysis of the SPI, the 'SCI' package from the software library R version 4.1.1 (R Core Team 2020) was used.

**Table 3**

***2.5. Multivariate Analysis***

The statistical technique of cluster analysis (CA) was applied to the pluviometric monthly temporal series (definition of homogeneous regions) and SPI-12 in Pakistan. This study applies the complete agglomerative hierarchical method to the 44 weather stations in the study area in a dendrogram (Wilks 2011). Moreover, the measure of dissimilarity is also calculated in this study using the square of the Euclidean distance (Eq. (10)) - (Lyra *et al.* 2014; Brito *et al.* 2017; Jardim *et al.* 2021).

$$d_e = \left[ \sum_{j=1}^{n} \left( P_{p,j} - P_{k,j} \right)^2 \right]^{0.5} \quad \textbf{(10)}$$

where $d_e$ is the Euclidean distance, and $P_{p,j}$ and $P_{k,j}$ are the quantitative variables $j$ of individuals $p$ and $k$, respectively.

We assessed the degree of adjustment of average linkage by utilizing the Cophenetic Correlation Coefficient (*CCC*). This coefficient measures the association between the dissimilarity matrix (phenetic matrix F) and the matrix resulting from the simplification provided by the grouping method (cophenetic matrix c). The *CCC* is based on the Pearson coefficient (*r*), calculated between the dissimilarity matrix and the matrix resulting from the grouping (Sokol and Rohlf 1962). Thus, the higher the r-value is, the less is distortion. Similarly, the dendrograms with *CCC* < 0.7 indicate the inadequacy of the CA technique (Sokol and Rohlf 1962; Oliveira-Júnior *et al.* 2017). The *CCC* is defined by Eq. (11).

$$CCC = r_{coph} = \frac{\sum_{i=1}^{n-1} \sum_{j>i}^{n} (c_{ij} - \bar{c})(d_{ij} - \bar{d})}{\sqrt{\sum_{i=1}^{n-1} \sum_{j>i}^{n} (c_{ij} - \bar{c})^2} \sqrt{\sum_{i=1}^{n-1} \sum_{j>i}^{n} (d_{ij} - \bar{d})^2}} \quad \textbf{(11)}$$

$$\bar{c} = \frac{2}{n(n-1)} \sum_{i=1}^{n-1} \sum_{j>i}^{n} c_{ij} \quad \textbf{(12)}$$

$$\bar{d} = \frac{2}{n(n-1)} \sum_{i=1}^{n-1} \sum_{j>i}^{n} d_{ij} \tag{13}$$

where $CCC$ is the cophenetic correlation coefficient, $c_{ij}$ and $d_{ij}$ are elements of the $i$-th row and $j$-th column of the cophenetic and the original distance matrix, respectively, and $n$ is the number of elements. Moreover, the $\bar{c}$ and $\bar{d}$ are the arithmetic averages of $c_{ij}$ and $d_{ij}$, respectively, as in Eqs. (12) and (13).

### *2.6. ENSO*

The Oceanic Nino Index (ONI), which is used to identify El Niño (warm phase), La Niña (cold phase), and ENSO Neutral events in the Tropical Pacific Ocean, was employed in the study (Huang *et al.* 2017). The ONI must have a value equal to or greater than the threshold for at least 3 consecutive 3-month periods of sea surface temperature (SST) exceeding 0.5°C for each occurrence classed as mild, moderate, strong, or very strong (NOAA/CPC 2021). Only the SPI-12 is used in this study to detect drought episodes on annual scales in time series, as well as their association with ENSO phases, which may be accessed at the following website: https://ggweather.com/enso/oni.htm.

### *2.7. Continuos Wavelet Transformation (CWT)*

The drought cycle periodicity was assessed using SPI time series. Since the SPI is calculated by using annual precipitation data, which make it is easy to infer. Using the gamma distribution, precipitation is simply transformed into a standard normal variable (Yerdelen 2021). In this study the variability in the data sets is identified using continuous wavelet transformation:

$$wf)(z,a) = \frac{1}{\sqrt{z}}\int_{-\infty}^{+\infty} f(x)\varphi^{*}\left[\frac{x-a}{z}\right]dx \quad \textbf{(14)}$$

here ‘a’ is the location parameter, ‘z’ is scaling factor, ‘ψ*’ corresponds to the complex conjugate of cwf and ‘f (x)’ refers to SPI time series. Wavelet scale changes with time and the translation factor gives rise to scalogram. When the predefined value is crossed by wavelet coefficients, the anomalous pattern is observed (Hafeez *et al.* 2022). Ideal threshold was retrieved by iterative process. The Morlet wavelet was implemented for decomposition of the SPI data series because it has the ability to decompose hydrological series in time and frequency (Rashid *et al.* 2015).

To study the variant pattern of precipitation in Pakistan on a time scale from 1980 to 2019 using wavelet transformation in different regions, the data is divided into four groups. The CWT convert 1-Dimensional signal which is time series data into time and frequency domains in 2-Dimensional space for the purpose of estimating the dominating and evident periodicity and turning points in SPI data series.

## 3. Results and Discussion

### *3.1. Climatology and Rainfall Seasonality*

In the 40 years of data, Pakistan's average annual rainfall demonstrated the establishment of a rainfall gradient from the South to the North, with variations ranging from 38.21 to 1596 mm (Figure 2). The Indian Ocean coastline influences the South, followed by lesser elevation values. The Balochistan

Plateau influences the North, Indus Plain, Hindu Kush, and Himalaya Mountains influence the North (Figure 1), with values exceeding 5000 m (Hussain and Lee 2009). According to Hussain and Lee (2009), the plains of Punjab and Sindh account for roughly 60% of all rainfall in Pakistan during the monsoon season. Monsoon rains are the most critical hydrometeorological resource (Eckstein *et al.* 2020; Hina *et al.* 2021).

This gradient causes variation in average annual rainfall, owing to the fact that Pakistan receives less rain than other South Asian nations (e.g., Bangladesh, Bhutan, India, Maldives, Nepal, and Sri Lanka) (Hussain and Lee 2016; Adnan *et al.* 2018; Hina *et al.* 2021). However, some stations in Pakistan stand out, such as Balakot (ID 4), Dir (ID 12), Islamabad (ID 18) - the country's capital; Kotli (ID 24); Murree (ID 29); Muzaffarabad Airport (ID 30); Parachinar (ID 35), and Sialkot (ID 41), all of which have annual rainfall records over 1000 mm (Table 1).

All of the above stations are in the country's north, in climatic zones A and B, as previously defined by Salma *et al.* (2012) and Hanif *et al.* (2013), who found that annual rainfall increased in the country's high latitudes, contrary to our findings, which revealed climatic diversity in Pakistan, according to the Köppen-Geiger classification, with a predominance of the category "BWh" — i.e. a warm desert (Figure 2).

**Figure 2**

Monthly rainfall in Pakistan fluctuates due to the rainfall gradient between South and North, which is connected with the monsoon wind regime and the disturbances in Western Pakistan (Salma *et al.* 2012), although the distribution of monthly rainfall in Pakistan is not uniform. Still, the rain doesn't fall all year long (Figure 3). During the months of July to September, Pakistan experiences monsoon rains that affect the country's eastern and northeastern regions. In the North and Northeastern regions of the country, there was a substantial amount of rainfall (Hussain and Lee 2016; Adnan *et al.* 2018; Hina *et al.* 2021). Notably, heavy monsoon-related rains, followed by flash floods and rivers, caused disasters in considerable part of Pakistan in 2010 (Sayama *et al.* 2012). From December to March, heavy rain fall on the region because of western disturbances from Iran and Afghanistan (Salma *et al.* 2012), which are then followed by the effect of Iran's Northern Mountains and the Balochistan Plateau. The wettest months are October to March (Hussain and Lee 2009).

**Figure 3**

### *3.2. Homogeneous Rainfall Regions*

The yearly rainfall series in Pakistan was clustered using seven different approaches in this study. The procedures were assessed using the CCC, which was subjected to a 5% significance level, as indicated in Table 4. Because the Complete approach was significant (S) and CCC > 0.9082, it stood out among the other techniques. Average, McQuity, and Centroid were three other approaches that stood out in the analysis, all of which had CCC > 0.90 and were all significant. The other approaches were ineffective, as the dendrogram was insufficient with a CCC of 0.70 (Sokol and Rohlf 1962; Wilks 2011; Oliveira-Jnior *et al.* 2017) and was not significant (NS).Ward's method is widely used in the scientific literature (Modarres and Sarhadi 2011; Brito *et al.* 2017; Oliveira-Júnior *et al.* 2017; Silva *et al.* 2021) and with the worst result for Pakistan.

**Table 4**

The sum of the squares of the clusters for the 44 evaluated stations (Figure 4a) allowed to identify an ideal number of four homogeneous groups in Pakistan. The dendrogram is shown in Figure 4b, with a percentage of 24.97% for the fenon line (cut line with the Euclidean distance) – (Wilks 2011; Brito *et al*. 2017) and the homogeneous pluviometric groups formed. Group $G_1$ (229.65 ± 109.48 mm) is the largest group formed with 34 stations, followed by group $G_2$ (1346.63 ± 285.98 mm) with four stations and groups $G_3$ (861.86 ± 225.37 mm) and $G_4$ (1171 ± 359.22 mm), with three stations (Table 5).

The $G_1$ group, despite the greater number of stations, had the lowest values of the median (209.29 mm), standard deviation (SD), and mean ($\bar{x}$), unlike the other groups, with the emphasis on the groups $G_2$ and $G_4$ with the higher median, SD and $\bar{x}$ values, as the seasons belong to the region with the highest rainfall records (Figure 2). The maximum, minimum and amplitude (AMP) values of the annual rainfall stood out in the $G_2$ group, with the minimum in the Dir station (ID 36 = 911.40 $mm.year^{-1}$), the maximum in the Murree station (ID 38 = 2433.80 $mm.year^{-1}$) and AMP = 1246.50 $mm.year^{-1}$ (ID 35 = Balakot), followed by the $G_4$ group, with minimum at Islamabad station (ID 42= 607.00 mm.year$^{-1}$), maximum at Parachinar station (ID 44 = 2356.80 mm.year$^{-1}$) and AMP = 1826.90 mm.year$^{-1}$ (ID 44). As for the exceptions, they were in the $G_3$ group, with the minimum at the Lahore station (PBO) (ID 40 = 333.70 mm.year$^{-1}$), the maximum at the Sialkot station (ID 38 = 1642.80 mm.year$^{-1}$) and AMP = 1642.00 mm .year$^{-1}$ (ID 41), and again the $G_1$ group stood out, with the lowest values between minimum (0 mm.year$^{-1}$), maximum (949.80 mm.year$^{-1}$) and AMP (187.60 mm.year$^{-1}$ ) – (Table 5).

Homogeneous groups were used for all of the coefficients of variation (CVs, %) below 100%. Thus, except for two seasons (ID 24 = 108.52 per cent and ID 25 = 102.49 per cent), all-time series data in group G1 were homogeneous (Wilks 2011; Gois *et al.* 2020). In contrast to the other groups, the G1 group had a larger prevalence of negative lower bounds in the exploratory statistics of yearly rainfall data at 21 sites. For G2 and G3 groups, the Murree (2501.34 mm.year$^{-1}$) and Balakot (746.55 mm.year$^{-1}$) stations were the upper and lower limits, respectively, while the Sialkot (1710.48 mm.year$^{-1}$) and Lahore stations were the G3 and G4 groups' lower and higher limits, respectively. However, there was a discrepancy between the maximum interquartile range (IQR) found in groups G2 (ID 24), G3 (ID 3), and G4 (237.98 mm.year-1, ID 28). (Table 5). . The non-parametric statistical tests of MK and Pettitt are the most critical instruments in time series analysis (Gois *et al.* 2020). The years 1998 (El Niño powerful) were found using the Pettitt test, indicating a 17-fold occurrence - (Table 5), 1991 (El

Niño Strong), 2004, and 2005 (El Niño strong) being the most significant occurrences in the time series. The years 2010 (La Nia Strong) and 2014 (El Niño Weak) were the exceptions – (NOAA/CPC 2021), in contrast to Hina *et al.* (2021), who identified 1987, 1991, 2000, 2001, 2002, and 2005 from the crossover of information between the SPI and the Single Z-Index. The El Niño of the Century (Slingo and Annamalai 2000) occurred during the 1997-98 cycle, and this El Niño, which was in the extreme category, caused a five-year drought throughout Southwest Asia, including Pakistan (ADB 2017; Ahmad *et al.* 2010; Ahmad *et al.* 2014; Hina *et al.* 2021). The Pettitt test identified the months with the ,most significant sudden changes in monthly rainfall in Pakistan, being March (7 changes), August and September (6 changes), and June and December (4 changes) – (Table 5). It is noteworthy that  June to September is considered the monsoon season in Pakistan, which contributes almost 57% of the total annual rainfall (Hussain and Lee 2016).

**Figure 4**

**Table 5**

The spatial distribution of homogenous groups revealed that the G1 group in southern and northern Pakistan has higher stations, from the coast to the region with the most remarkable hypsometry totals (Figure 5). The G2 group lies near the plateau and plains, while the G3 and G4 groups are towards the mountain range's base. The transitional rainfall regime in Pakistan is characterized by the least rainy group (G1) between the coast and the mountain range and the wettest groups (G2, G3, and G4) in the north and windward parts of the mountain range.

**Figure 5**

As an example, in the south, north, and northwest, where the highest mountains in the world (peak K2-8200 m) are located, homogeneous groupings are dispersed according to the country's physiography. Pakistan's Indus plains, Punjab and Sindh, are considered to be central, while the deserts of the southeast and the dry lands of southwest are considered to be peripheral (Chaudhry and Rasul 2004). Droughty conditions are found in 60 percent of the country according to the Köppen-Geiger classification "BWh" (Figure 1). The climate is characterised by a hot, dry summer and a cold, snowy winter in the Himalayas. In the central region, semi-arid to dry conditions prevail, whereas coastal areas have their own distinct climate (Karim *et al.* 2020).

### *3.3. SPI anual*

- ***Spatial***

The prevalence of the very and extremely dry categories was seen in the spatial distribution of SPI-12 in the years identified by the Pettitt test. In the years 2005 and 2010, there are exceptions. In 2005, the category near to normal predominated in the eastern part of Pakistan. Still, in 2010 it prevailed in the western part of the nation, with occurrences of the same and highly humid categories in the country's extreme north, where the highest elevations are found (Figure 1). In the years 1991, 2004, and 2014, severely dry conditions were observed in the regions of Balochistan, Sindh, and Punjab, as opposed to highly wet conditions in particular Pakistani regions in the years 2005 and 2010 (Figure 1).

According to ONI (Huang *et al.* 2017; NOAA/CPC 2021), the years 1991 (El Niño Strong), 1998 (El Niño Very Strong), the 2004/2005 cycle (transition between El Niño Weak and La Niña Weak), 2010 (El Niño Moderate), and 2014 (El Niño Moderate) Weak had an impact on the dynamics of drought in Pakistan. The main advantage of the SPI is that it can be calculated in a temporal multiscale (Mckee *et al.* 1993; Kim *et al.* 2014; Mishra and Singh 2010) and can be used to assess the impacts of rainfall deficits as well as to compare different locations (Carmo and Lima 2020; Costa *et al.* 2021; Gonçalves *et al.* 2021). Pakistan is divided into tropical and subtropical zones, with arid regions accounting for 75 percent of the total landmass (mainly in the South) and making it more vulnerable to drought (Adnan 2016).

**Figure 6**

El Niño events were analysed using the Pettitt test, and the geographical analysis based on SPI-12 was examined for the years of Very Strong El Niño events (Huang *et al.* 2017; NOAA/CPC 2021) - (Figure 7). According to the SPI in Table 3, in Pakistan in the 1982/83 cycle, there were higher records of the categories very dry and close to normal. There were a few exceptions to this rule in 1982, when exceptionally humid and dry conditions were prevalent in the north of the country. It's worth noting that in 1983, the extremes of Pakistan saw a particularly dry period, while the middle of the country experienced a period close to usual. For the first time, data from an Asian precipitation grid (APHRODITE - Asian Precipitation Highly-Resolved Observational Data Integration Towards Evaluation) was used to calculate the SPI, and the PCA (Principal Component Analysis) was used to identify droughts in Pakistan's central and southern regions. Between 1998 and 2002, Pakistan had a severe drought as a result of the 1997/98 El Niño (ADB 2017; Ahmad *et al.* 2010; Ahmad *et al.* 2014; Slingo and Annamalai 2000; Hina *et al.* 2021). In 1997, the extremes of the country had the most dry conditions, followed by the interior, which had the most humid conditions. This contrasted with 1998, when the extremes of the country had the most dry conditions and the interior had the most humid conditions. There was a predominance of the category similar to normal, followed by fairly dry and occasionally severely humid categories in 2015. The very dry and extremely dry weather categories dominated in 2016, as they did in 1998. According to Chaudhry and Rasul (2004), Pakistan has around two-thirds of its land covered by semi-arid and arid climates. The results obtained also match the findings of Hanif *et al.* (2013), where they found that Southwest Pakistan is especially vulnerable to drought.

**Figure 7**

- ***Temporal***

Pakistan's homogeneous rainfall groups are depicted in Figure 8 using the SPI-12 temporal distribution. In the time series, SPI-12 oscillations revealed dry and wet seasons. In this study, we focused only on assessing drought in homogeneous populations. As a result of the G1 group, Baldin and Karachi (Airport) stations are included, where the SPI-12 category is close to normal, followed by some years categorised as very dry (SPI-12 -1.0), for example, the years 1989 (La Niña Strong), 1991 (El Niña Strong), 1996 (La Niña Moderate), 2002 (El Niño Moderate) and 2006 (La Niña Weak), the exceptions were the years 1987 and 2018 - (Table 3). As in G1, the Dir and Murree stations fall into the G2 group, which has a high prevalence of this category, but with a higher degree of variation among these stations in this category. Aside from a year classified as extremely dry in 2018 in Dir season, the other years were 1984/1985 (La Niña Weak), 1987/1988 (El Niño Strong) and 1999 (La Niña Strong) – (Huang *et al.* 2017; NOAA/CPC 2021).

This group, which includes Lahore (PBO) and Sialkot stations, is similar to the previous groups, with the exception of 2002 (El Niño Moderate), which was categorised as extremely dry – SPI-12 – in the Lahore (PBO) station in the years 1987 (El Niño Strong), 1993/94 (La Nia Strong), 1999/2000 (La Niña Strong), 2004/05 (El Niño Weak), and 2009/2010 (El Niño Moderate) (Table 3). Of all of the stations studied over time, only the years 1987 (El Niño Strong) and 2009 (El Niño Moderate) at the Sialkot station had significant drought occurrences - (Huang *et al.* 2017; NOAA/CPC 2021). A similar pattern is seen in G4 group, with the Islamabad and Parachinar stations, with the Islamabad station showing a predominance of the category near normal, followed by SPI-12's 'extremely dry' category, except for year 2009, when the Parachinar station showed the majority of drought events in the 1980s, except for 1999/2000. According to Hina *et al.* (2021), 1987, 1991, 2000, 2001, 2002, and 2005 are the years in which the SPI and the Single Z-Index cross information in the temporal evaluation.

According to Khan and Gadiwala (2013), public managers should pay attention to drought episodes in the country since the country has been struggling with water scarcity (Xie *et al.* 2013), which is exacerbated by drought and brings social and economic impacts and increased social vulnerability (Ahmed *et al.* 2018; Adnam *et al.* 2018).

**Figure 8**

### *3.4. Annual rainfall Trend*

Statistical analysis of rainfall trend (Figure 9) via MK test (Z and $Z_{MK}$) showed that most of the stations used in the study were observed in the NSIT rainfall category (Table 2) throughout Pakistan, the exceptions were in the stations in the south (category SRT – Dir – ID 12, Jiwani – ID21 and Dalbandin – ID10) and in the North (category STI - Gilgit – ID15, Gupis – ID16, Khanpur (Pbo) – ID23, Lasbella – ID26, Moen-Jo-Daro – ID27 and Parachinar – ID35) - (Table 5). The values obtained from $Z > 0$ and p–value > 0.05 of probability were only in the stations that were categorized as STI and SRT, on the contrary, in the rest of the country with the predominance of conditions of $Z < 0$ and p – value < 0 .05

probability, mainly in the Balochistan Plateau (Figure 1). Spatially, the annual rainfall reduction trend is concentrated in the north and south sectors, that is, obeying the previously identified rainfall gradient (Figure 2), and conversely, increasing trends were observed in specific sectors existing in the country in the last 40 years. The results obtained agree with the results obtained by Salma *et al.* (2012), who showed a significant downward trend in rainfall, however, only in 20 years of the series, followed by the results of Hanif *et al.* (2013), which showed that annual rainfall significantly increased in Pakistan's high latitudes.

It is noteworthy that the MK test is the most appropriate method for locating and approximately detecting the starting point of a given trend, being the most suitable method for analyzing climate change in time series (Gois *et al.* 2020; Terassi *et al.* 2020). The non-significant increase in the magnitude of rainfall in Pakistan, according to Sen's method, was recorded mainly in homogeneous groups G2, G3 and G4, the exception being group G1 (Table 5).

**Figure 9**

### *3.5. CWT Analysis*

In a signal the patterns that progress over time are identified while applying time-localized filtering that encourages to identify spectral characteristics. To categorize the interrelation of wavelet coefficient with every signal component, the wavelet maps are retrieved. The periodicity and their spatial localization, the continuous wavelet power spectrum offered an approximate idea.

The analyses for annual SPI for 40 years over 8 cities were considered as a continuous series, interesting patterns can be observed. For the purpose of long-term trend detection, the 40 year (1980-2019) was subdivided into 4 groups i.e., Group 1 (Badin, Karachi) - Group 2 (DIR, Murree), Group 3 (Lahore, Sialkot) and Group 4 (Islamabad, Parachinar). In G1, the Karachi station retrieved SPI data showed positive behavior during first 5 years of analyzed data followed by less precipitation condition in year 1987 (Fig. 10b), Badin station also showed similar pattern of SPI data. During the year 1991 and 1996, the drier weather conditions were classified overall, but in Karachi the SPI values were higher as compared to Badin (Fig. 10a).

In G2 the Dir station shows interspersed dry years while the years 2005, 2010, and 2012 marked somewhat wet surroundings (Fig. 10c). Wherein 2014 and 2015 showed extreme rainfall values that lead to less dry conditions in 2017 and extreme pattern during 2018. Whereas the apted station in Murree recorded moderate dry conditions roughly during 2005 to 2010, and the year 2015 showed extreme rainfall i.e., adequate number of rainfall followed by dry conditions (negative SPI) for next 4 years (Fig. 10d). The group 3 which includes Lahore and Sialkot showed dry conditions in 1993 accompanied by wet conditions during 1995 which then turns in to extreme wet for 1996 and 1997 (Figs. 10e and 10f). During year 2003 Lahore depicted moderately dry condition i.e., negative SPI values, while Sialkot recorded positive SPI values i.e., wet conditions. During the last years (2017-2019), we observed the transition from dry to wet conditions meaning by significant increase in rainfall level gradually. While considering group 4 we observed continuous dry conditions during second decade of our considered data in Parachinar but in comparison to this behavior Islamabad station showed dispersed rainfall throughout the data (Figs. 10g and 10h). During 2010 and onwards we also measured extreme rainfall values for Parachinar stations and Islamabad replicated scattered values of SPI.

**Figure 10**

## 4. Conclusions

The comprehensive approach is applied precisely to Pakistan's historical precipitation data. As a result of the study's statistical criteria, the average, McQuitty, and centroid techniques can all be applied. Cluster analysis is used to identify four distinct rainfall categories in Pakistan (G1, G2, G3, and G4). Highlight for the largest group G1, with lower values obtained from descriptive and exploratory statistics compared to the other groups.The Pettit test applied to Pakistan's rainfall temporal data indicates that El Niño years in the Strong category contribute to drought variability. In Pakistan, the Pettitt test shows that March, August, September, June, and December are the months with the highest change in rainfall. These months should be monitored by public managers in Pakistan to the greatest extent possible.

SPI-12 categorises the performance of the Strong and Very Strong El Niños in Pakistan into relatively dry and close to normal categories. SPI-12 once again reveals that Pakistan's rainy seasons are dominated by the categories "near to normal" and "very dry," but severely dry years occur in the country, and these years in particular demand attention by Pakistani managers.

It has been observed that the Mann-Kendall test shows non-significant increases in Pakistan's rainfall, with the exception of a few seasons in the southern and northern regions of Pakistan. It is apparent that the non-significant increase in Pakistan's rainfall is of concern to numerous sectors of society, such as planning and management territory, agricultural, tourist, commerce and urban drainage and water resources management, as well as the economy, tourism and agriculture.

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## Conflict of Interest

The authors declare no conflicts of interest.

## Ethics approval/declarations

There is no ethical conflict by all authors.

## Consent to participate

All authors agree to participate.

## Consent for publication

All authors agree with the publication.

## Code availability

Not applicable.

## Authors' contributions

Shahid I. and G. Gois analyzed the raw data and revised the original draft, Shahzad R., M. Silva and A. Jardim performed the data analysis, created the figures and J. Oliveira-Júnior, A. Souza, M. Shah and A. Abbas prepared the draft of the original article.

### References


ADB, 2017. Climate risk and vulnerability analysis report. Baluchistan water resources development Project preparatory technical assistance (TA 8800-PAK). Asian Development Bank, Government of Balochistan, JICA Japan and Techno-Consult International.

Adnan S. 2010. Spatio-Temporal Distribution of Drought and its Characteristics over Pakistan (Doctoral dissertation, COMSATS University Islamabad, Islamabad, Pakistan).

Adnan S, Ullah K, Shuanglin L, Gao S, Khan AH, Mahmood R. 2010. Comparison of various drought indices to monitor drought status in Pakistan. *Climate Dynamics* **51**(1): 1885–1899. DOI: 10.1007/s00382-017-3987-0

Ahmad I, Ambreen R, Sultan S, Sun Z, Deng W. 2014. Spatial-temporal variations in January precipitation over the period of 1950-2000 in Pakistan and possible links with global teleconnections: geographical perspective. *American Journal of Climate Change* **3**(4): 378–387. DOI: 10.4236/ajcc.2014.34033

Ahmad I, Zhaobo S, Weitao D, Ambreen R. 2010. Trend analysis of January temperature in Pakistan over the period of 1961-2006: Geographical perspective. *Pakistan Journal of Meteorology* **7**(1):11–22.

Anjum SA, Saleem MF, Cheema MA, Bilal MF, Khaliq T. 2012. An assesment to vulnerability, extent, characteristics and severity of drought hazard in Pakistan. *Pakistan Journal of Meteorology* **64**(1):85-96.

Beguería S, Vicente-Serrano SM, Reig F, Latorre B. 2010. Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *International Journal of Climatology* **34**(): 3001-3023. DOI: 10.1002/joc.3887

Brito TT, Oliveira-Júnior JF, Lyra GB, Gois G, Zeri M. 2017. Multivariate analysis applied to monthly rainfall over Rio de Janeiro state, Brazil. *Meteorology and Atmospheric Physics* **129**(5): 469-478. DOI: 10.1007/s00703-016-0481-x

Carmo MVNS, Lima CHR. 2020. Caracterização Espaço-Temporal das Secas no Nordeste a partir da Análise do Índice SPI. *Revista Brasileira de Meteorologia* **35**(2): 233-242. DOI: 10.1590/0102-7786352016

Chaudhry, Q. Z., Rasul, G., 2000. Agroclimatic classification of Pakistan, Science Vision, 9(1–2 & 3–4), (July–Dec, 2003 & Jan–Jun, 2004), 59.

Costa, MS, Oliveira-Júnior JF, Santos PJ, Correia Filho WLF, Gois G, Blanco CJC, Silva Junior CA, Santiago DB, Souza EO, Jardim, AMRF. 2021. Rainfall extremes and drought in Northeast Brazil and its relationship with El Niño–Southern Oscillation. *International Journal of Climatology* **41**(S1): E2111–E2135. DOI: 10.1002/joc.6835

Eckstein D, Künzel V, Schäfer L, Winges M. 2020. Global climate risk index. Bonn: Germanwatch, pp. 1-43.

Fung KF, Huang YF, Koo CH, Soh YW. 2020. Drought forecasting: A review of modelling approaches 2007–2017. J. *Water & Climate Change* **11**(3): 771–799. DOI: 10.2166/wcc.2019.236

Gois G, Oliveira-Júnior JF, Silva Junior CA, Sobral BS, Terassi PMB, Leonel Junior AHS. 2020. Statistical normality and homogeneity of a 71-year rainfall dataset for the state of Rio de Janeiro—Brazil. *Theoretical and Applied Climatology* **141**(1): 1573–1591. DOI: 10.1007/s00704-020-03270-9

Gonçalves STN, Vasconcelos Junior FC, Sakamoto MS, Silveira CS, Martins E SPR. 2021. Índices e Metodologias de Monitoramento de Secas: Uma Revisão. *Revista Brasileira de Meteorologia* **36**(3): 495-511. DOI: 10.1590/0102-7786363000

Hanif M, Khan AH, Adnan S. 2013. Latitudinal precipitation characteristics and trends in Pakistan. *Journal of Hydrology* **492**(7): 266-272. DOI: 10.1016/j.jhydrol.2013.03.040

Hafeez A, Ehsan M, Abbas A, Shah M, Shahzad R. 2022. Machine learning-based thermal anomalies detection from MODIS LST associated with the Mw 7.7 Awaran, Pakistan earthquake. *Natural Hazards*. DOI: 10.1007/s11069-021-05131-8

Heim Jr. RR. 2002. A review of twentieth-century drought indices used in the United States. *Bulletin of the American Meteorological Society* 83(8): 1149-1166. DOI: 10.1175/1520-0477-83.8.1149

Ho S, Tian L, Disse M, Tuo Y. 2021. A New Approach to Quantify Propagation Time from Meteorological to Hydrological Drought. *Journal of Hydrology* **603** (Part B): 127056. DOI: 10.1016/j.jhydrol.2021.127056

Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., ... & Zhang, H. M., 2017. Extended reconstructed sea surface temperature, version 5 (ERSSTv5): upgrades, validations, and intercomparisons. *Journal of Climate* **30**(20): 8179-8205. DOI: 10.1175/JCLI-D-16-0836.1

Hussain MS, Lee SH. 2009. A Classification of Rainfall Regions in Pakistan. *Journal of the Korean Geographical Society* **44**(5): 605-623.

Jardim AMRF, Silva MV, Silva AR, Santos A, Pandorfi H, Oliveira-Júnior, JF, Lima JLMP, Souza LSB, Araújo Junior GN, Lopes PMO, Moura GBA, Silva TGF. 2021. Spatiotemporal climatic analysis in Pernambuco State, Northeast Brazil. *Journal of Atmospheric and Solar-Terrestrial Physics* **223**(1): 105733. DOI: 10.1016/j.jastp.2021.105733

Karim R, Tan G, Ayugi B, Babaousmail H, Liu F. 2020. Evaluation of Historical CMIP6 Model Simulations of Seasonal Mean Temperature over Pakistan during 1970–2014. *Atmosphere* **11**(9):1005. DOI: 10.3390/atmos11091005

Kendall, M. G. Rank correlation methods, London: Charles Griffin. 1975.

Khan MA, Gadiwala, MS. 2013. A Study of Drought over Sindh (Pakistan) Using Standardized Precipitation Index (SPI) 1951 to 2010. *Pakistan Journal of Meteorology* **9**, 15-22.

Kim CJ, Park MJ, Lee JH. 2014. Analysis of climate change impacts on the spatial and frequency patterns of drought using a potential drought hazard mapping approach. *International Journal of Climatology* **34**(1): 61-80. DOI: 10.1002/joc.3666

Lyra GB, Oliveira-Júnior JF, Gois G, Cunha-Zeri G, Zeri M. 2017. Rainfall variability over Alagoas under the influences of SST anomalies. *Meteorology and Atmospheric Physics* **129**(1): 157-171. DOI: 10.1007/s00703-016-0461-1

Lyra GB, Oliveira-Júnior JF, Zeri M. 2014. Cluster analysis applied to the spatial and temporal variability of monthly rainfall in Alagoas state, Northeast of Brazil. *International Journal of Climatology* **34**(13): 3546-3558. DOI: 10.1002/joc.3926

Mann HB. 1945. Non-parametric test against trend. *Econometrica* **13**(1): 245-259. DOI: 10.2307/1907187

McKee TB, Doesken NJ, Kleist J. 1993. The relationship of drought frequency and duration to time scales. In: *Proceedings of the 8$^{th}$ Conference on Applied Climatology*, 17, 179-183.

Mishra AK, Singh VP. 2010. A review of drought concepts. *Journal of Hydrology* **391**(1-2): 202-216. DOI: 10.1016/j.jhydrol.2010.07.012

Modarres R. Sarhadi A. 2011. Statistically-based regionalization of rainfall climates of Iran. *Global and Planetary Change* **75**(1): 67-75. DOI: 10.1016/j.gloplacha.2010.10.009

NOAA/CPC - National Oceanic and Atmospheric Administration/Climate Prediction Center. 2021. Cold & Warm Episodes by Season. [online]. Available at: <http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml>. [Accessed 21 November 2021].

Oliveira Júnior JF, Lyra GB, Gois G, Brito TT, Moura NDSHD. 2012. Análise de homogeneidade de séries pluviométricas para determinação do índice de seca IPP no estado de Alagoas. *Floresta e Ambiente* **19**(1): 101-112. DOI: 10.4322/floram.2012.011

Oliveira-Júnior JF, Gois G, Lima Silva IJ, Oliveira Souza E, Jardim AMRF, Silva M V, Jamjareegulgarn P. 2021. Wet and dry periods in the state of Alagoas (Northeast Brazil) via Standardized Precipitation Index. *Journal of Atmospheric and Solar-Terrestrial Physics* **224**(1): 105746. DOI: 10.1016/j.jastp.2021.105746

Oliveira-Júnior JF, Xavier FMG, Teodoro PE, Gois G, Delgado RC. 2017. Cluster analysis identified rainfall homogeneous regions in Tocantins state, Brazil. *Bioscience Journal (On line)* **33**(1): 333-340. DOI: 10.14393/BJ-v33n2-32739

Pettitt AN. 1979. A non-parametric approach to the change-point problem. *Journal of the Royal Statistical Society Series C (Applied Statistics)* **28**(1): 126-135. DOI: 10.2307/2346729

R Core Team., 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rashid MM, Beecham S, Chowdhury RK. 2015. Assessment of trends in point rainfall using Continuous Wavelet Transforms. *Advances in Water Resources* **82**(1):1-15. DOI: 10.1016/j.advwatres.2015.04.006

Salma S, Rehman S, Shah MA. 2012. Rainfall Trends in Different Climate Zones of Pakistan. *Pakistan Journal of Meteorology* **9**(17): 37-47.

Sayama T, Ozawa G, Kawakami T, Nabesaka S, Fukami K. 2012. Rainfall–runoff–inundation analysis of the 2010 Pakistan flood in the Kabul River basin. *Hydrological Sciences Journal* **57**(2): 298–312. DOI: 10.1080/02626667.2011.644245

Silva MV, Pandorfi H, Jardim AMRF, Oliveira-Júnior JF, Divincula JS, Giongo PR, Silva TGF, Almeida GLP, Moura GBA, Lopes PMO. 2021. Spatial modeling of rainfall patterns and groundwater on the coast of northeastern Brazil. *Urban Climate* **38**(1): 100911. DOI: 10.1016/j.uclim.2021.100911

Slingo JM, Annamalai H. 2000. 1997: The El Niño of the Century and the Response of the Indian Summer Monsoon. *Monthly Weather Review* **128**(6): 1778–1797. DOI: 10.1175/1520-0493(2000)128<1778:TENOOT>2.0.CO;2

Sokal RR, Rohlf FJ. 1962. The comparison of dendrograms by objective methods. *Taxon* **11**(2): 33-40. DOI: 10.2307/1217208

Terassi PMB, Oliveira Júnior JF, Gois G, Galvani E, Sobral BS, Biffi VHR. 2020. Analysis of daily rainfall and spatiotemporal trends of extreme rainfall at Paraná slope of the Itararé watershed, Brazil. *Revista Brasileira de Meteorologia* **35**(2): 357-374. DOI: 10.1590/0102-7786352025

Ullah I, Ma X, Yin J, Asfaw TG, Azam K, Syred S, Liu M, Arsahd M, Shahzaman M. 2021. Evaluating the meteorological drought characteristics over Pakistan using in situ observations and reanalysis products. *International Journal of Climatology* **41**(9): 4437– 4459. DOI: 10.1002/joc.7063

Wilks DS. 2011. Statistical Methods in the Atmospheric Sciences. 3rd Edition, Academic Press, Oxford, 704.

WMO – World Meteorological Organization. Standardized precipitation index user guide. 2012. Available in: <http://www.wamis.org/agm/pubs/SPI/WMO_1090_EN.pdf>. Access on: 24 Nov. 2021.

Xie H, Ringler C, Zhu T, Waquas A. 2013. Droughts in Pakistan: a spatiotemporal variability analysis using the Standardized Precipitation Index. *Water International* **38**(5): 620-631. DOI: 10.1080/02508060.2013.827889

Yerdelen C, Abdelkader M, Eris E. 2021. Assessment of drought in SPI series using continuous wavelet analysis for Gediz Basin, Turkey. *Atmospheric Research* **260**(1): 105687. DOI: 10.1016/j.atmosres.2021.105687

Zargar A, Sadiq R, Naser B, Khan FI. 2011. A review of drought indices. *Environment Review* **19**(1): 333-349. DOI: 10.1139/a11-013

# Figures

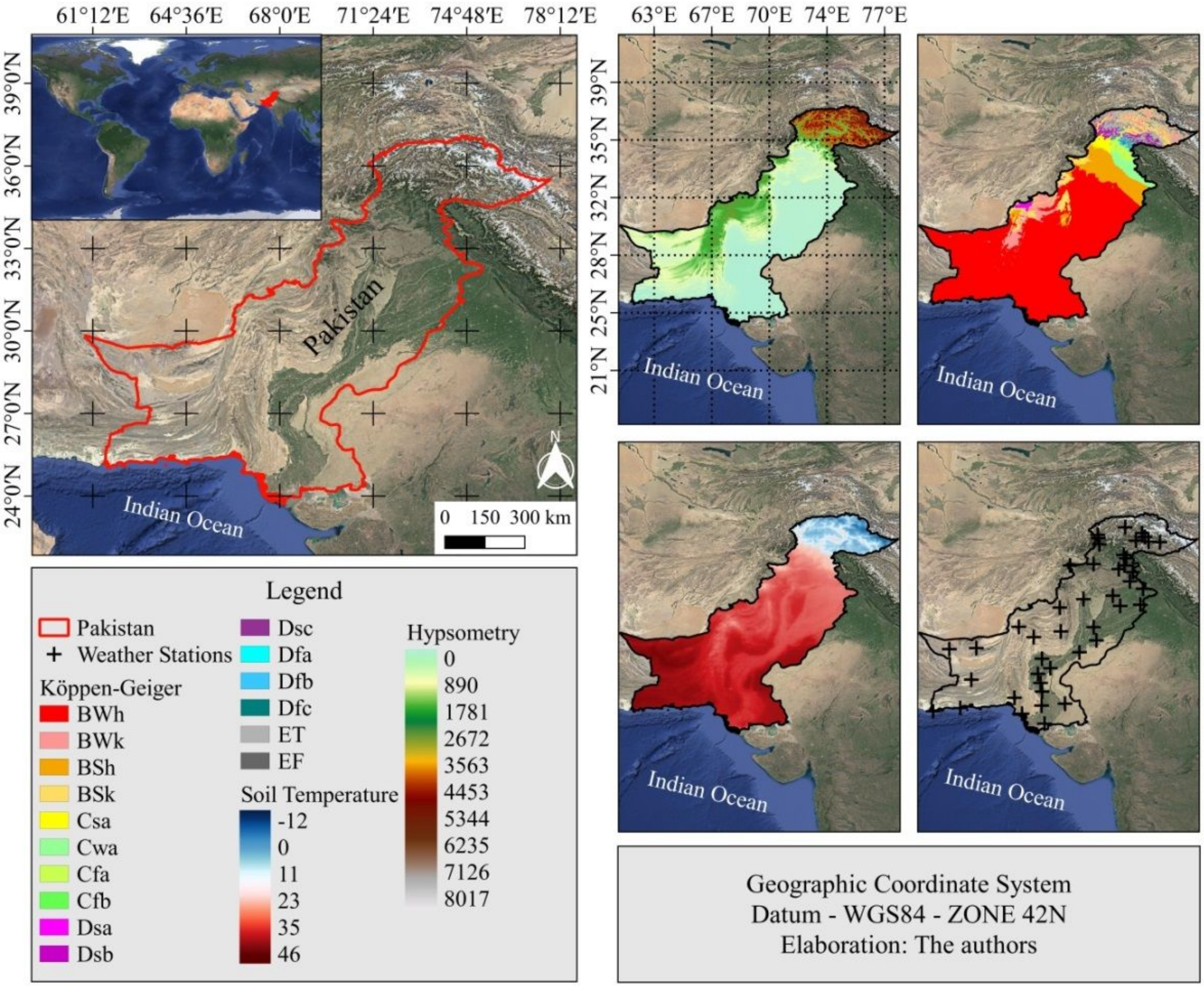
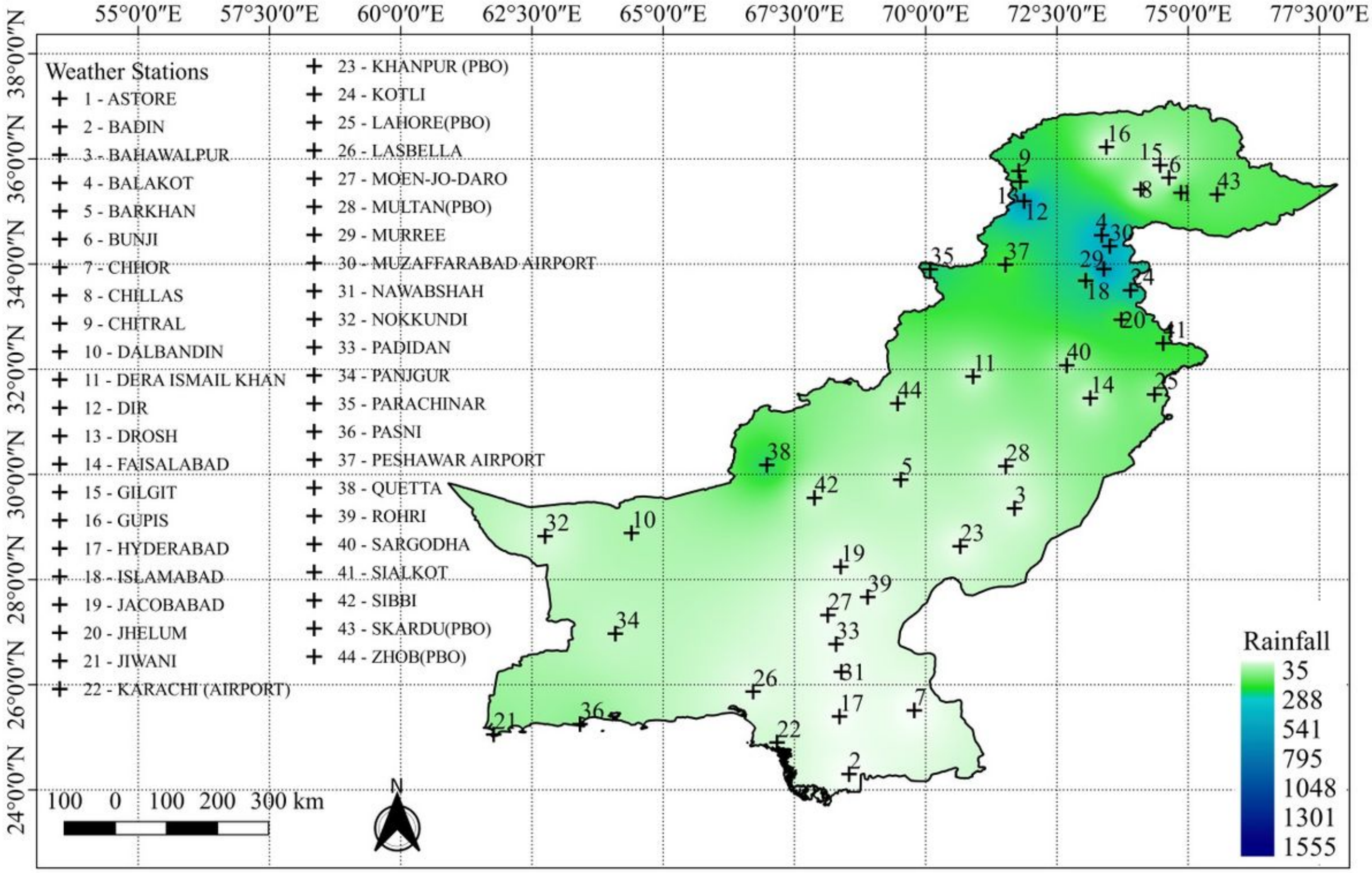


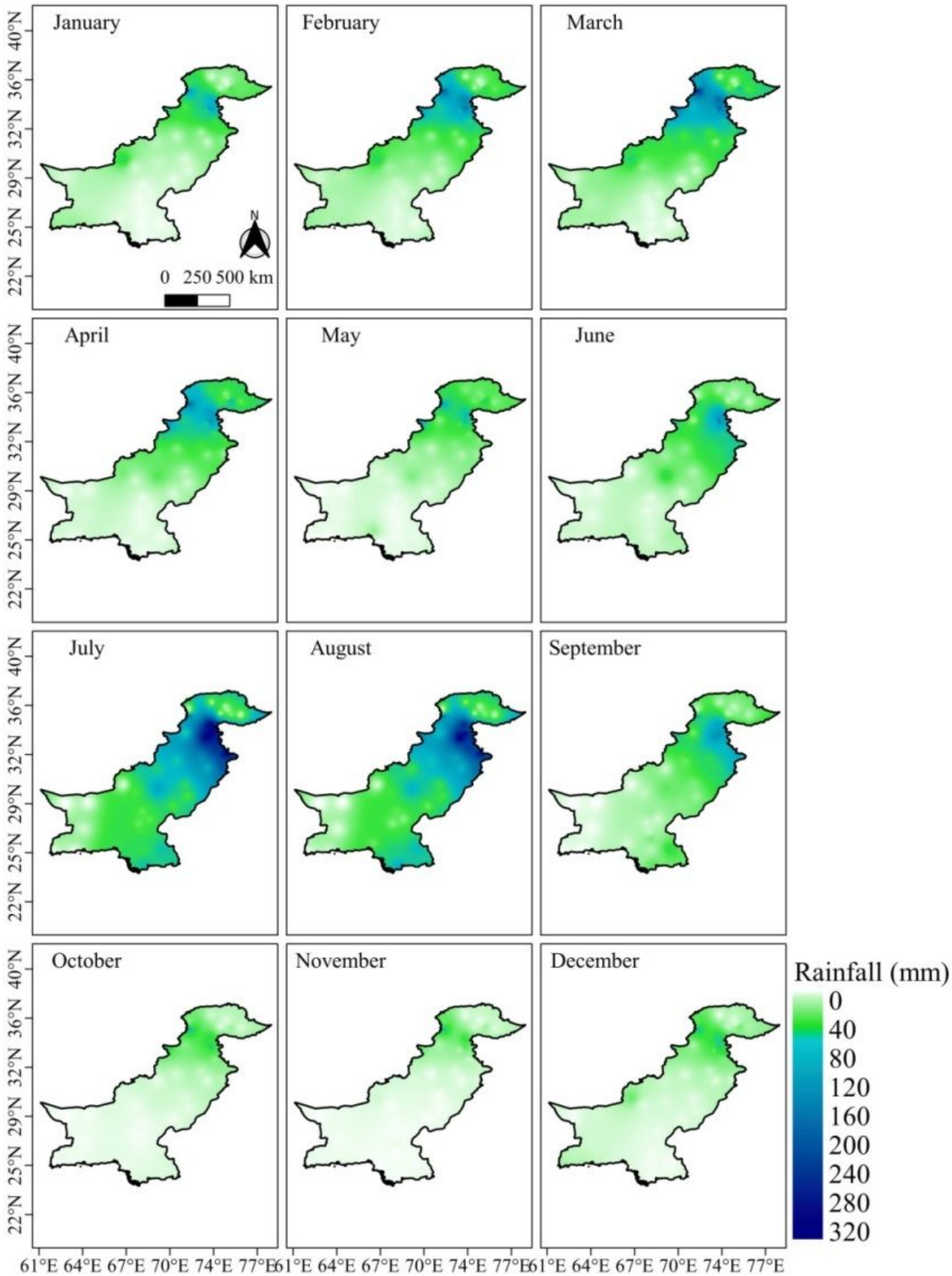

**Figure 1**

The location map of the weather stations (+), climate classifcation on the basis of de Köppen-Geiger, temperature in in (ºC) via MODIS product (SRTM - Shuttle Radar Topography Mission, 30 m).




## Figure 2

Spatial distribution of mean annual rainfall (mm/year) in Pakistan during 1980-2019.




## Figure 3

Spatial distribution of mean monthly rainfall (mm.month$^{-1}$) in Pakistan during 1980-2019.

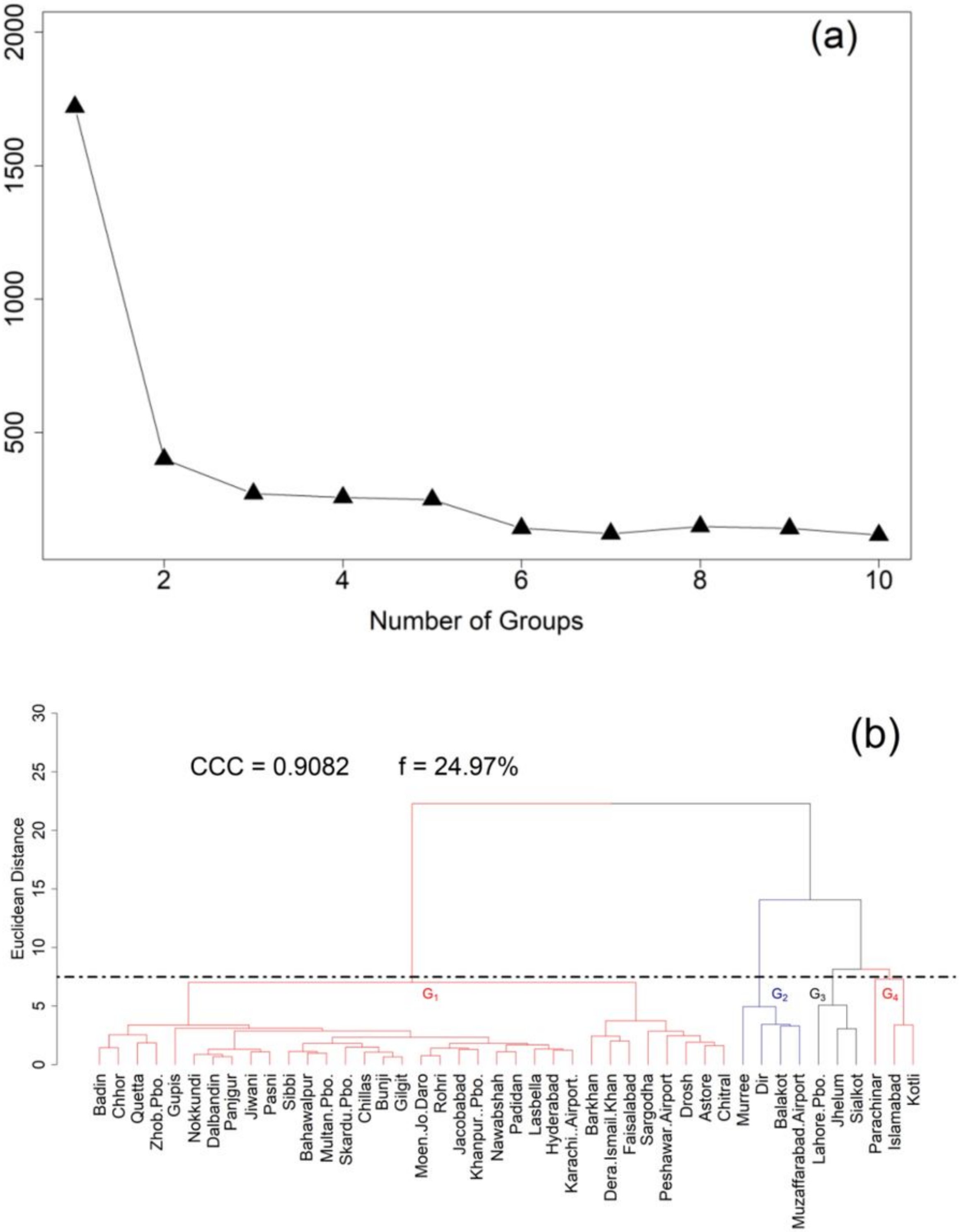
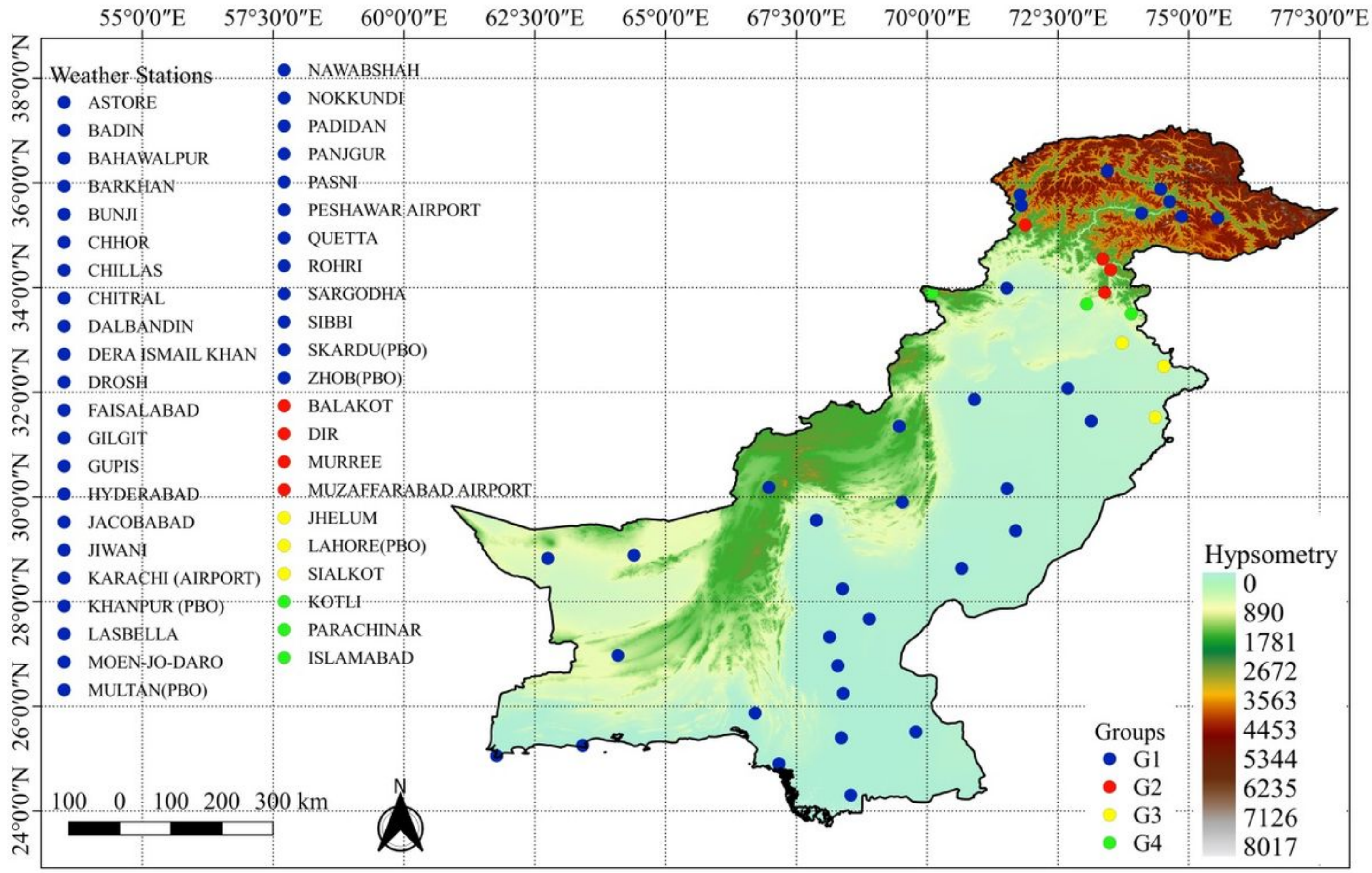


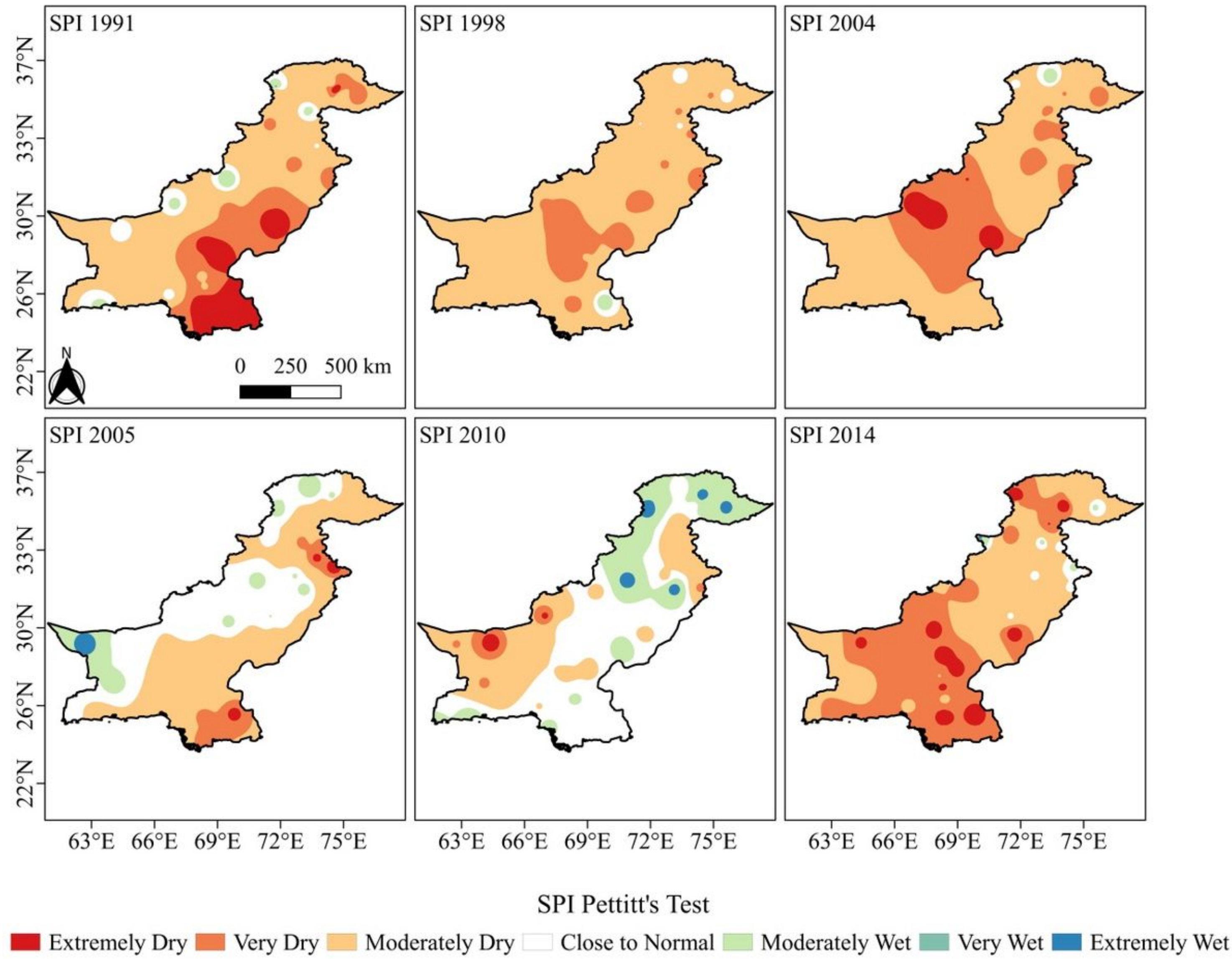

**Figure 4**

(**a**) Sum of Squares of the Groups, and (**b**) average connection in the form of a dendrogram for homogeneous groups of rainfall ($G_1$, $G_2$, $G_3$, and $G_4$) for the 44 weather stations in Pakistan during 1980-2019.



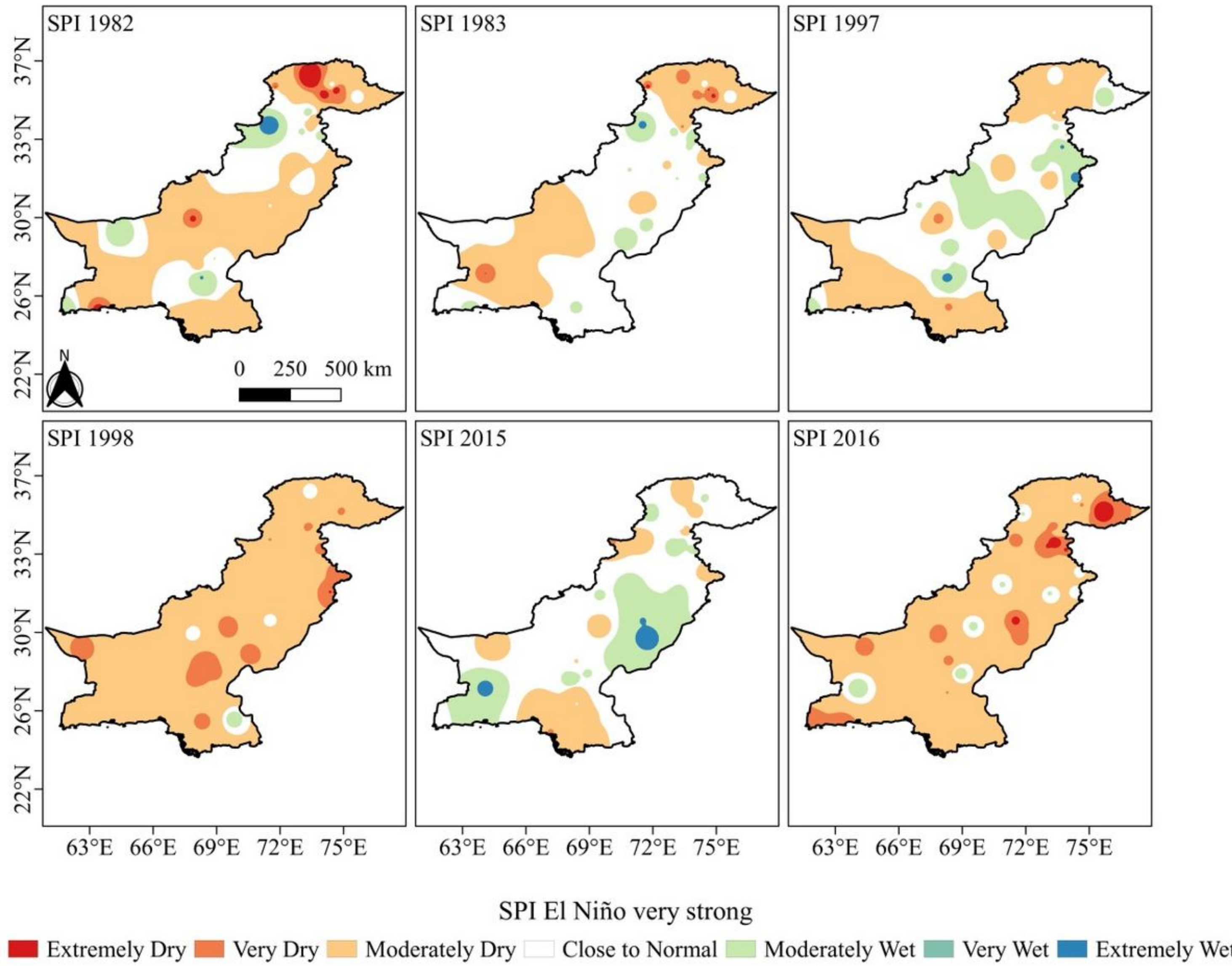

## Figure 5

Pakistan's spatial distribution of homogeneous rainfall groups (G1, G2, G3, and G4) and its hypsometry (m).



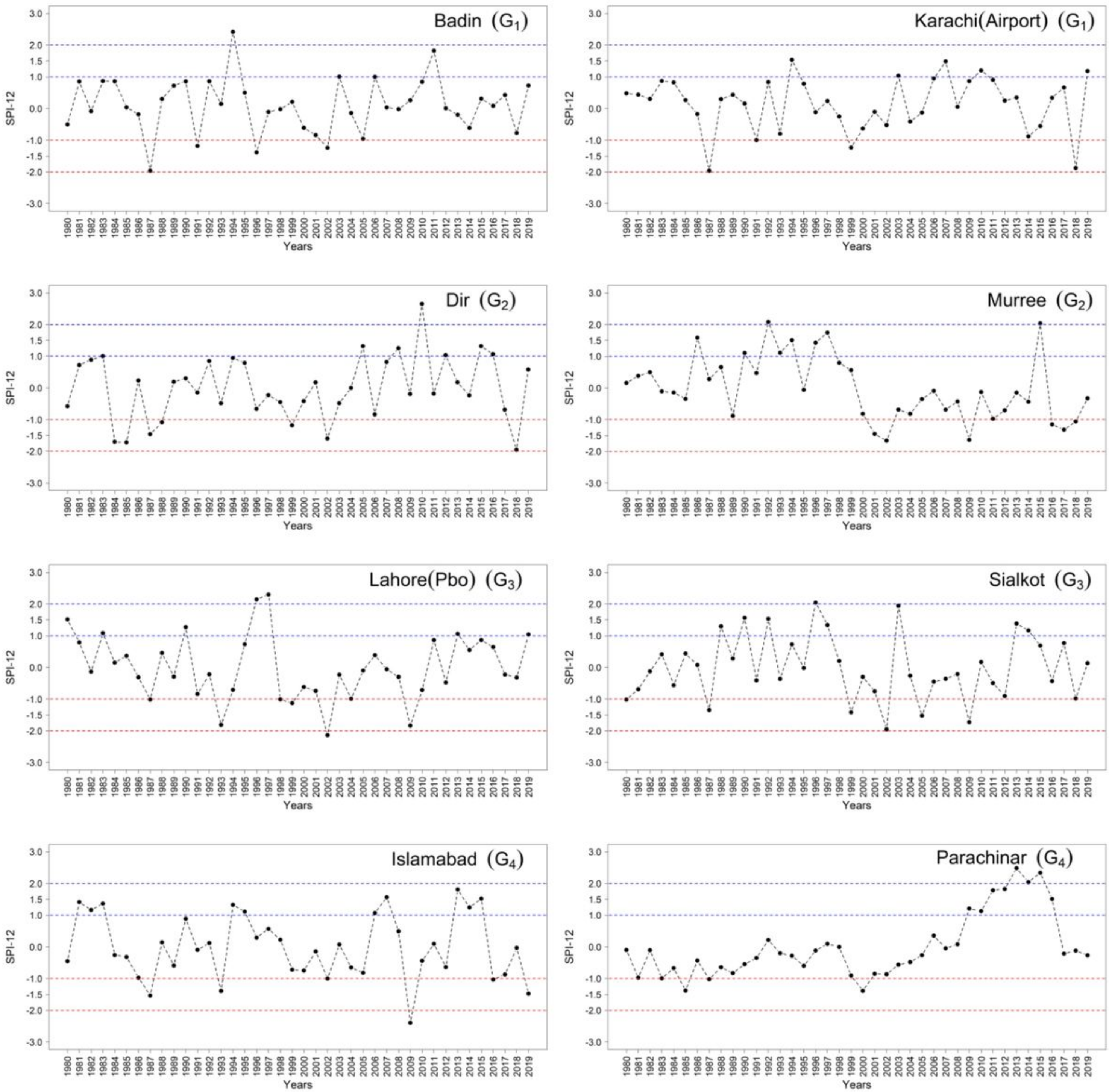

#### Figure 6

According to the Pettitt test, the spatial distribution of SPI-12 in Pakistan in the years 1991, 1998, 2004, 2005, 2010 and 2014.




## Figure 7

Special distribution of SPI-12 in the years of El Niño events in the very strong category, according to Oceanic Niño Index (ONI) in Pakistan.




## Figure 8

SPI-12 temporal distribution of homogeneous rainfall groups ($G_1$, $G_2$, $G_3$ and $G_4$) during 1980-2019.

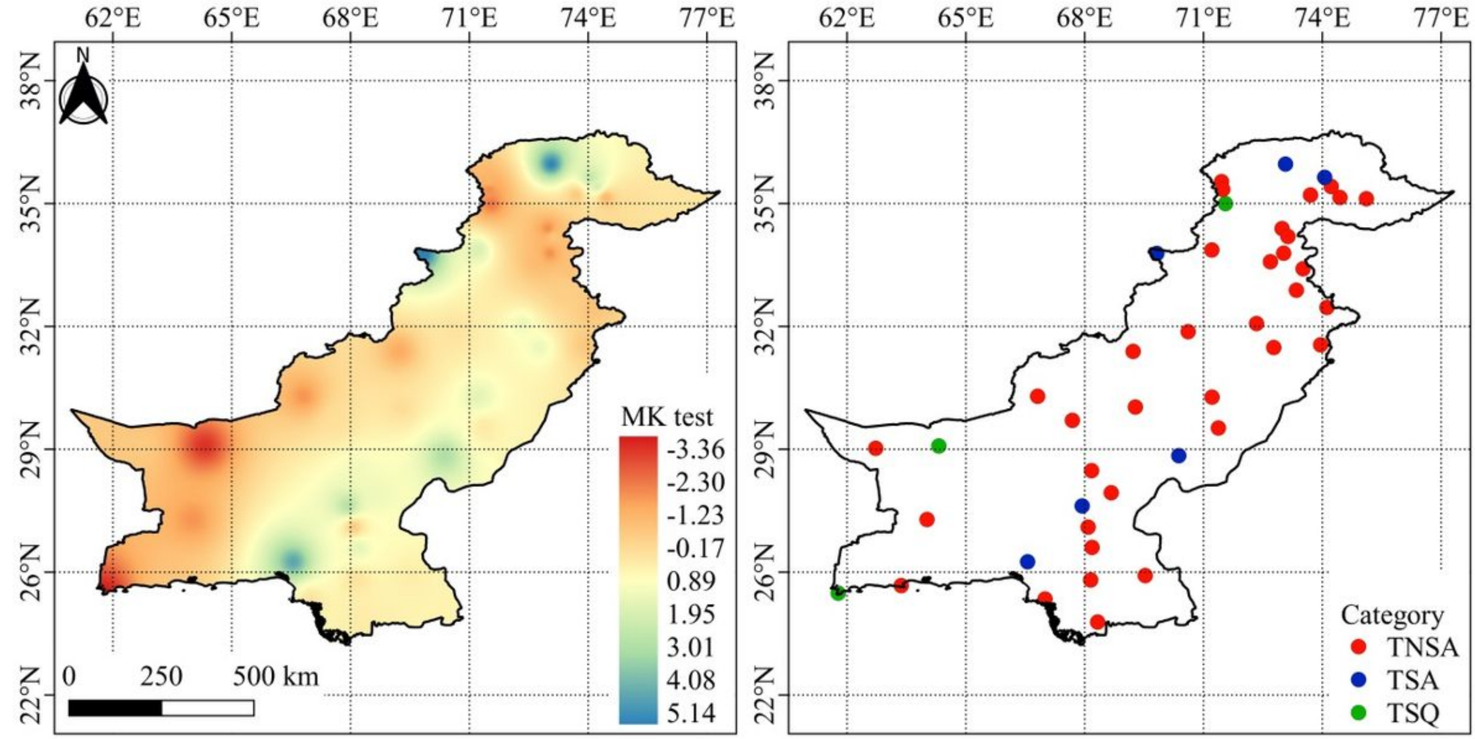



**Figure 9**

Annual rainfall trend (mm) in Pakistan based on Mann-Kendall (MK) test results versus Z value (**left side**) and its $Z_{MK}$ categories (**right side**) in the period 1980-2019.

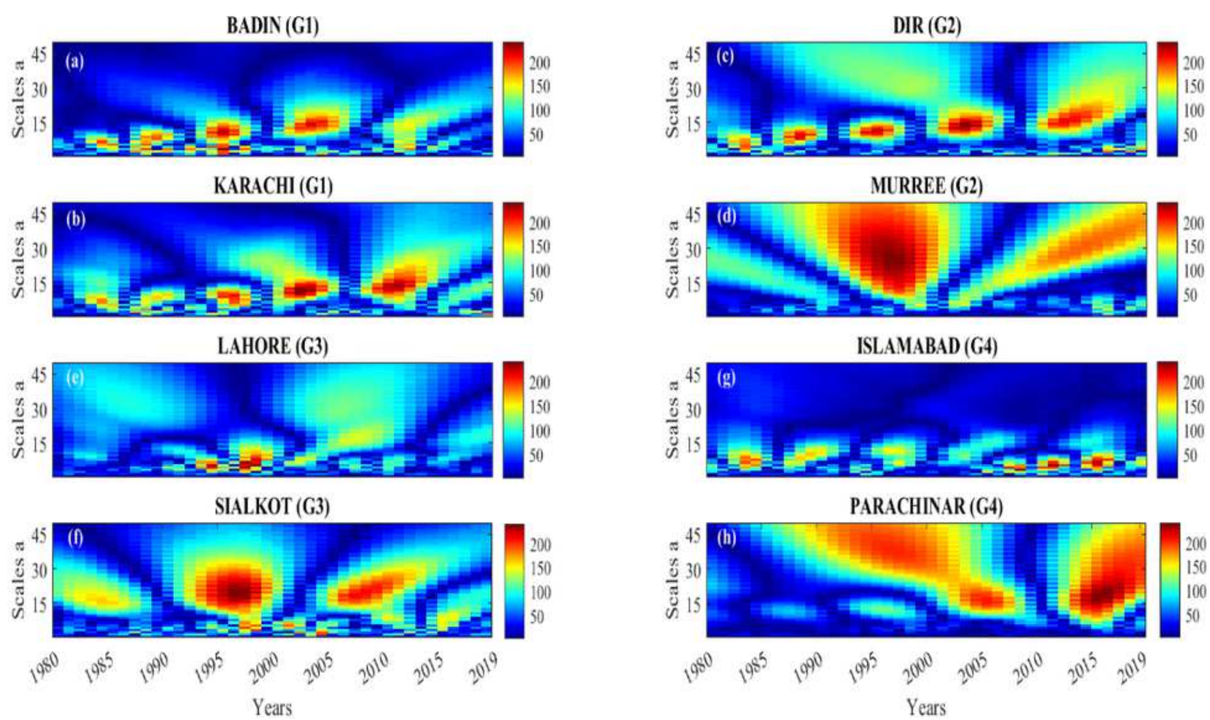



**Figure 10**

Annual SPI trend in Pakistan from 1980 to 2019.