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Title: Clustering of Rainfall Stations and Distinguishing Influential Factors using PCA and HCA Techniques over Western Dry Region of India

Running Head: Rainfall Stations' Clustering and Their Influential Factors

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ABSTRACT

This study used hierarchical cluster analysis (HCA) to delineate spatial patterns of monthly, seasonal and annual rainfall by clustering 62 stations in western arid region of India based on 55-year (1957-2011) dataset. Statistical properties of clusters were computed, and box-whisker plots were plotted. Furthermore, relative influence of three geographical factors, i.e., longitude, latitude and altitude, and five statistical parameters, i.e., mean, standard deviation (SD), coefficient of variation (CV), maximum and minimum rainfall, on mean rainfall was investigated using principal component analysis (PCA). HCA resulted in four rainfall clusters geographically located at a distinct position. Cluster-I, characterized by the lowest mean rainfall and highest CV, was located in western portion, whereas, mean rainfall was the highest for cluster-IV, situated in eastern portion. Box-whisker plots revealed slight skewness although monsoon and annual rainfall followed the normal distribution. PCA results indicted 2-3 significant principal components (PCs) with eigenvalues of more than one. In four clusters, first 2 PCs explained the major variance ranging from 69.41% (June) to 91.83% (August) in monthly, 63.62% (monsoon) to 93.30% (post-monsoon) in seasonal, and from 71.48 to 90.73% in annual rainfall. In monthly and seasonal rainfall, PC 1 is termed 'mean rainfall component', which has strong to moderate associations of longitude, and equally opposed by CV. These findings are vital for planners and decision-makers to formulate strategies to manage unusual rainwater quantities.

Keywords: Arid region; Geographical factors; Hierarchical cluster analysis; Principal component analysis; Rainfall; Statistical parameters.

1. INTRODUCTION

Rainfall, primary water source for global agriculture, is highly variable over space and time, and is an indicator for climate variability/change (Frich et al., 2002). Thus, knowledge about spatial pattern of rainfall is essential for sustainable agricultural water management and to detect climate variability. Importance of spatial pattern recognition is high for the low rainfall areas especially arid and semi-arid regions encompassing about 35% (>61 million km^2) of global lands (Mares, 1999). The Indian arid region, encompassing over 38.7 million ha, experiences both hot and cold climates (Kar et al., 2009). Of total hot-arid lands, a major part (28.57 million ha) exists in the northwest portion of the country with low, uncertain, and highly variable rainfall (Kar et al., 2009). Therefore, it is imperative to understand spatial rainfall patterns in the region.

In literature, several methods have been used for investigating spatial rainfall patterns, e.g. L-moments (Guttman, 1993), harmonic analysis (Suhaila and Jemain, 2009), multivariate regression (Sabziparvar et al., 2015), spatial correlation functions (Şen and Habib, 2001), spatial interpolation (Gupta et al., 2017), k-means clustering (Machiwal et al., 2017), empirical orthogonal functions (Jebari et al., 2009), Pearson's correlation (Haines and Olley, 2017), regional frequency analysis (Medina-Cobo et al., 2017), support vector machines (Lin et al., 2017), among others. Spatial pattern recognition by cluster analysis (CA) and principal component analysis (PCA) are other methods to find homogenous rainfall clusters (Modarres and Sarhadi, 2011). Amissah-Arthur and Jagtap (1999) applied PCA and CA to seasonal rainfall of Nigeria for clustering 23 stations into 6 groups. Decreasing rainfall trends in 4 delineated groups were identified. Golian et al. (2010) compared natural break and revised fuzzy c-means methods by clustering 25 stations using 1975-2008 rainfall for northern Iran and indicated coherence between outcomes of both methods. In Iran, regional rainfall patterns were quantified using CA and L-moments together using annual rainfall of 137 stations for 1952-2003 (Modarres and Sarhadi, 2011). In other study, Nnaji et al. (2016) grouped 24 rainfall stations into 5 clusters in Nigeria based on coefficient of variation (CV) through hierarchical cluster analysis (HCA). Furthermore, linkages between mean annual rainfall and CV resulted in linear, power law and logarithmic relationships. Recently, Machiwal et al. (2017) classified 32 stations of hot and cold Indian arid regions into entirely-arid and partially-arid clusters, based on 102-year (1901-2002) rainfall using k-means clustering. Results indicated prominent increasing trends in annual and wet season rainfall for entirely-arid cluster. In literature, studies combining PCA and HCA to delineate rainfall clusters and to identify major factors associated with clusters are rare (e.g., Darand and Daneshvar, 2014).

This study was undertaken with two objectives: (i) delineating rainfall clusters by HCA and understanding their spatial patterns at monthly, seasonal and annual scales in northwest hot-arid lands of India, and (ii) identifying influential geographical and statistical factors by PCA. This study is the first of its kind in finding significantly-influencing factors to spatial rainfall patterns by PCA in HCA-delineated clusters.

2. STUDY AREA AND DATA DESCRIPTION

Western dry region of India (study area), lying to west of Aravalli Hills, is located between latitudes 24º37'00" and 30º10'48" N, and longitudes 69º29'00" and 76º05'33" E. The study area comprises 12 districts of Rajasthan State namely Barmer, Bikaner, Churu, Hanumangarh, Jaisalmer, Jalor, Jhunjhunu, Jodhpur, Nagaur, Pali, Sikar, and Sriganganagar (Fig. 1). Despite the climate adversity, a major portion of the Indian arid lands falls in the study area (62% of hot-arid lands) (Kar et al., 2009). Climate is characterized by low annual rainfall (100-500 mm) and high potential evapotranspiration (1400-2000 mm) (Moharana et al., 2016). In summer, the mean maximum temperature ranges from 40-42°C with May being the hottest month. In winter, the mean monthly maximum temperature ranges from 22-29°C and minimum temperature from 4-14°C (Moharana et al., 2016).

Daily rainfall data of 55-year (1957-2011) for 62 stations, acquired from Water Resources Department, Government of Rajasthan, India, were used to prepare monthly, seasonal and annual series. This study considered four monsoon months, i.e., June, July, August, and September, and four seasons, i.e., monsoon (JJAS), post-monsoon (OND), winter (JF), and pre-monsoon (MAM). Longitude and latitude of stations were located on study area map (Fig. 1). Missing data for some stations in few years was estimated by inverse distance weighting method.

3. MATERIALS AND METHODS

3.1 Hierarchical Cluster Analysis of Rainfall Series

CA helps in grouping variables into clusters according to the high similarity of their features such as geographical, physical, statistical or stochastic properties (Modarres and Sarhadi, 2011). CA is of two types: hierarchical and non-hierarchical (Otto, 1998). HCA is the common approach where clusters of variables are sequentially formed where each cluster depicts the least variance (or smallest dissimilarity) of variables. This study considered Ward’s agglomerative hierarchical algorithm (Ward, 1963) as dissimilarity measure using the Euclidean distance, as follows (Everitt and Dunn, 1991):

$$d_e = \left[\sum_{i=1}^{n}\left(P_{p,i} - P_{q,i}\right)\right]^{1/2} \tag{1}$$

Where, d_e = Euclidean distance; and $P_{p,i}$ and $P_{q,i}$ are quantitative variables i of individuals p and q, respectively.

HCA was performed for monthly, seasonal and annual rainfall by using STATISTICA software (StatSoft Inc., 2004).

3.2 Computing Statistical Properties of Delineated Rainfall Clusters

Salient statistics, i.e., mean, SD, CV, skewness and kurtosis, were computed for rainfall clusters of monthly, seasonal and annual series. Furthermore, box-whisker plots were drawn to explore cluster-wise summary of five key statistics along with outliers and extremes (USEPA, 1998).

3.3 Exploring Relationship of Geographical and Statistical Factors with Rainfall

This study investigated linear relationship between mean rainfall and geographical and statistical parameters by computing correlation coefficient for two pairs prior to identify the major factors dominating each cluster. Three geographical variables, i.e., longitude, latitude and altitude, and four statistical factors, i.e., SD, CV, minimum and maximum of the rainfall, were considered to find the extent of relationship between these variables and the mean rainfall of monthly, seasonal and annual series.

3.4 Applying PCA to Identify Dominating Features/Components for Rainfall Clusters

PCA is used to reduce dimensionality to get an economic description of rainfall profile where differences between various profiles may be clearly evidenced (Davis, 2002). PCA helps recognizing patterns by explaining the variance of a large set of inter-correlated variables, and transforms them into a smaller set of independent factors (PCs) (Dillon and Goldstein, 1984). Significant PCs were chosen by Kaiser (1958) criterion (eigenvalue>1), which best describe variance of analyzed variables with reasonable interpretation (Harman, 1960).

Rainfall $R(i,j)$ at i^{th} station and in j^{th} year is expressed as the sum of products of the coefficients $A_n(i)$ varying over space, and associated temporal pattern or eigenvectors $B_n(j)$, as follows (Gadgil and Iyengar, 1980):

$$R(i,j) = \sum_{k=1}^{n} [A_n(i)] \times [B_n(j)] \quad (2)$$

Where, $i = 1, \ldots, N$; and $j = 1, \ldots, n$, and $B_n(j)$ = eigenvectors of correlation matrix.

This study applied PCA to geographical and statistical parameters of stations grouped under clusters. Stations altitude was taken from digital elevation model of Shuttle Radar Topographic Mission. PCA aimed at finding relative influence of each variable explaining variance of the system in each separate cluster for monthly, seasonal and annual series.

4. RESULTS AND DISCUSSION

4.1 Clustering of Rainfall Stations

HCA delineated four clusters of 62 stations for monthly, seasonal and annual series, which were geographically located over space (Fig. 2). It is seen that stations exist in close proximity to each other in every cluster. Likewise, clustering resulted in geographical contiguity of stations in some of the delineated groups in Nigeria (Amissah-Arthur and Jagtap, 1999). Also, clusters depict a definite geographical pattern justifying clustering. It is observed that spatial pattern of clusters slightly varies over months, seasons and year along with variation in number of stations in every cluster. A careful examination revealed that stations of cluster-I are mainly situated towards the western portion of area in most months, seasons and year (Fig. 2). On contrary, stations of cluster-IV are mainly located in the eastern portion. Likewise, cluster-III exists in the northern and northeast portions, whereas cluster-II is seen towards the southern portion.

4.2 Statistical Properties of Rainfall Clusters

Cluster-wise statistics of the mean rainfall over months, seasons and year are presented in Table 1. The mean rainfall remains the lowest in cluster-I and the highest in cluster-IV except in August, September, and pre-monsoon season. In general, SD of rainfall is the least for cluster-I and the most for cluster-II. Both skewness and kurtosis values for all clusters of annual rainfall are within the permissible limits (±2.0) for normal distribution. Similarly, skewness and kurtosis are within normality limits for July, August and September, and monsoon season except for single cluster over these periods. However, the mean rainfall deviates from normality in all clusters during June and post-monsoon. Positive skewness indicates that rainfall is slightly right-skew in all clusters in all periods. It is further revealed that both the mean monthly rainfall and SD are the highest in August in all clusters although CV is comparatively low in July indicating least temporal variations. In monsoon, the mean and SD are the highest with least amount of rainfall variations (CV<45%) in all clusters in comparison to other three drier seasons with contrasting statistics. CV remains the lowest (35-42%) in annual rainfall in comparison to that in months and seasons. This indicates that rainfall variations are relatively high over the shorter periods of months and seasons containing scanty rainfall.

Box-whisker plots of four clusters for monthly, seasonal and annual scales are depicted in Figs. 3(a-c). The median rainfalls are the lowest for cluster-I in June, July and September months, and for cluster-III in August. An important finding is that the larger length of the upper whisker compared to the lower whisker, and presence of outliers and extremes towards the upper whisker. This indicates that distribution of monthly rainfall is right-skewed, which is in agreement with the results of skewness values. Among seasons, rainfall distribution is more uniform in pre-monsoon and winter as revealed from less outliers/extremes in comparison to post-monsoon (Fig. 3b). Among all periods, monsoon and annual rainfall are more uniformly-distributed over time, and follow normality (Fig. 3c). It is evident that cluster-wise patterns are quite comparable for monsoon and annual rainfall (Fig. 3c). The lowest median rainfall values are in cluster-I while the medians of clusters II and IV are relatively high although rainfall distribution in cluster-II is more uniform as outliers/extremes are absent (Fig. 3c).

4.3 Rainfall Correlations with Geographical Factors and Statistical Parameters

Correlation coefficients (R) are presented in Table 2. The minimum rainfall was mostly zero in monthly and seasonal rainfalls, and thus, was not analyzed. The mean rainfall of June is strongly correlated ($R>0.70$) with longitude, altitude and SD, and is moderately correlated ($R>0.50$) with maximum rainfall. This finding suggests that monsoon rains are quite good at higher altitudes near the upper portion of the Aravalli range. Similarly, rainfall of July has very strong correlation ($R>0.80$) with SD, strong correlation with maximum rainfall, and moderate correlation with longitude, altitude and CV. August rainfall is strongly related to SD, and moderately related to altitude and maximum rainfall. R-values in September indicate very strong linkages of mean with SD and maximum rainfall. Among seasons, monsoon and post-monsoon rainfall revealed very strong correlations with SD, and moderate correlations with longitude and altitude. In addition, maximum rainfall has strong and moderate relations with mean values in monsoon and post-monsoon, respectively. Winter rainfall is very strongly correlated to longitude and SD, strongly correlated to latitude and CV, and moderately correlated to maximum rainfall. Whereas, pre-monsoon mean rainfall is strongly related to longitude, latitude, SD and CV, and moderately related to maximum rainfall. In annual rainfall, R-value suggests very strong relationships with SD and minimum rainfall, strong with maximum rainfall, and moderate with longitude and altitude. It is inferred that SD has very strong to strong relationships with mean rainfall of every month, season and year. However, rainfall linkages with CV and latitude are strongly related only in winter and pre-monsoon. Similar findings are reported for Nigeria where monthly rainfall has power law relationship with CV (Nnaji et al., 2016). Looking at moderate to very strong linkages of geographical and statistical parameters with mean, this study subsequently used PCA to identify influential geographical and statistical parameters dominating each cluster.

Prior to applying PCA, Gleason-Staelin redundancy measure (Gleason and Staelin, 1975) and Bartlett's test of sphericity (Bartlett, 1950) were used to evaluate appropriateness of the variables to be used as inputs to PCA. Value of the redundancy measure for four clusters was found to vary from 0.43-0.67 for monthly, from 0.39-0.71 for seasonal and from 0.44-0.60 for annual series. This indicates a moderate to good correlation among the variables. Furthermore, results of Bartlett's chi-squared test-statistics were found statistically-significant ($p<0.05$) for all clusters of monthly, seasonal and annual series. Hence, the null hypothesis that correlation matrix is an identity matrix was to be rejected, which suggested that the variables are appropriate to perform PCA.

4.4 Significant Principal Components for Rainfall Clusters in Individual Months

The PCA resulted in 6-8 principal components (PCs) in clusters although only first 2 or 3 PCs were found significant following the Kaiser's criterion of eigenvalue more than 1. A major portion of the variance was mostly explained by first two PCs for monthly (75.36-88.44% for June, 69.41-83.53% for July, 74.60-91.83% for August, and 73.70-86.58% for September), seasonal (63.62-90.39% for monsoon, 81.82-93.30% for post-monsoon, 75.74-88.60% for winter, and 64.31-77.77% for pre-monsoon) and annual series (71.48-90.73%) (Figs. 4-6). Thus, factor coordinates of the variables for first two PCs were plotted against each other on the unit circle plots to subsequently examine their associations with two significant PCs (Fig. 4) for four monthly clusters.

To scrutinize variables associated with two significant PCs, their coordinates were classified into strong (PC-coordinate≥0.75) and moderate (0.75>PC-coordinate≥0.50) associations following criteria of Liu et al. (2003) (Table 3). In most monthly clusters, mean (Avg) has either strong or moderate association with PC 1 that is steadier than that with PC 2. Hence, PC 1 is termed 'mean rainfall component' (Table 3). In June, cluster-I is characterized by strong positive association of mean rainfall, longitude, strong negative association of latitude and CV, whereas cluster-II is characterized by strong negative association of longitude, altitude, mean and CV, moderate negative association of latitude, mean and maximum rainfall. In cluster-III, strong positive association of latitude, strong negative association of longitude, altitude, mean, SD, maximum rainfall, and moderate positive association of CV characterize PC 1. However, PC 1 of cluster-IV is characterized by strong positive linkage of longitude, latitude, altitude, mean, strong negative linkage of CV, moderate negative linkage of SD and maximum rainfall. In July, PC 1 of cluster-I has strong positive association of mean, negative association of CV, moderate positive association of longitude, altitude and SD while cluster-II represents strong positive associations of longitude, altitude, negative association of CV, moderate positive association of mean. PC 2 of cluster-III in July depicts moderate negative associations of altitude, mean, SD and maximum rainfall, whereas, cluster-IV reveals strong positive linkages with longitude, altitude, mean, strong negative linkage with CV, moderate positive latitude, and negative maximum rainfall. For August, cluster-I represents strong positive association of longitude and mean, strong negative association of latitude and CV, and moderate negative maximum rainfall. Cluster-II is contributed by strong positive latitude, strong negative mean, SD, CV and maximum rainfall. In cluster-III, PC 2 corresponds to strong negative coordinates of altitude and mean, and moderate negative coordinate of SD while PC 1 of cluster-IV is represented by strong negative coordinates of altitude, mean, SD and maximum rainfall. In September, PC 1 of cluster-I is characterized by moderate positive relationship with latitude, strong negative relations of mean, SD and maximum rainfall. Whereas, the PC 2 of cluster-II is characterized by strong positive coordinate of altitude, moderate positive coordinates of longitude, mean and SD. Similarly, PC 2 of cluster-III is characterized by strong positive relations of longitude, altitude, mean, moderate positive coordinate of SD, strong negative coordinate of latitude, and moderate negative coordinate of

CV. However, PC 1 of cluster-IV is characterized by strong positive coordinates of longitude, altitude, mean and SD, moderate positive coordinate of maximum rainfall, strong negative coordinates of latitude and CV.

Overall, it is apparent that maximum rainfall and SD of monthly rainfall mostly remain close to each other. This indicates that SD should be higher for a month having higher maximum rainfall, and vice versa. Further, CV on the unit circle plot is always opposed by mean suggesting that months having low rainfall exhibit large variations.

4.5 Dominating Factors Associated with Clusters of Seasonal and Annual Rainfall

The unit circle plots were drawn between first two significant PCs for seasonal (Fig. 5) and annual (Fig. 6) rainfall. On two PCs, the strong and moderate associations of variables for seasonal rainfall are summarized in Table 4. Similar to months, the mean rainfall over seasons has strong association with PC 1 in most clusters and seasons, and thus, the PC 1 is termed 'mean rainfall component'. It is seen that cluster-I of monsoon rainfall has strong associations of longitude (negative), CV (positive), moderate association of mean (negative), SD (positive), and maximum rainfall (negative). Whereas, cluster-II has strong coherence of longitude, altitude, mean, maximum, strongly opposed by CV. Cluster-III has strong linkages of altitude, SD, and moderate linkage of the mean that is opposed by moderate linkage of latitude, while cluster-IV is strongly linked to longitude, altitude, mean, maximum rainfall, moderately to latitude, and strongly opposed by CV. Likewise, for post-monsoon, cluster-I is strongly related to longitude, mean, SD, moderately to altitude and maximum rainfall, moderately opposed by CV. Cluster-II has strong linkages with mean, SD, CV, maximum rainfall, and moderately to altitude, whereas, cluster-III is strongly linked to longitude, altitude, mean, that is strongly opposed to latitude, and moderately to CV. Whereas, cluster-IV is strongly associated to longitude, altitude, mean, SD, moderately to maximum rainfall, which is opposed by strong linkage of latitude, and moderate of CV. In winter, cluster-I is strongly related to longitude, altitude, mean, and moderately to SD. In cluster-II, PC 1 has strong association of longitude, latitude, altitude, and mean, which is strongly opposed by CV. PC 1 in cluster-III is contributed by strong positive coordinates of latitude and mean, moderate coordinates of SD and maximum rainfall, which is opposed by moderate coordinates of latitude and CV. Cluster-IV has strong linkages of longitude and mean, moderate linkage of altitude, which is strongly opposed by CV. In pre-monsoon, PC 1 of cluster-I is represented by strong coordinates of mean and SD, moderate coordinates of longitude, altitude and maximum rainfall that is moderately opposed by CV, whereas, cluster-II is strongly favoured by longitude, latitude, mean and SD, moderately favoured by altitude, and strongly opposed by CV. However, PC 2 of cluster-III is characterized by strong negative coordinate of mean and moderate negative coordinate of latitude, while cluster-IV has strong associations of mean and SD. It is evident that the maximum rainfall and SD for all clusters in the seasons remain close to each other, which is in agreement with finding of the monthly rainfall. Another prominent feature is that CV, distinctly located to other variables, is mostly opposed by latitude and mean.

In annual rainfall (Fig. 6), PC 1 of cluster-I has strong positive associations of longitude, mean and maximum rainfall, moderate of latitude, and strongly opposed by CV. For cluster-II, PC 1 has strong negative linkages of longitude, altitude, mean, and minimum, moderate negative linkage of maximum rainfall, strongly opposed by CV (Table 4). In cluster-III, PC 2 is characterized by strong negative coordinates of longitude and mean, and moderately negative by minimum and maximum rainfall. On the other hand, cluster-IV has PC 1 characterized by strongly positive longitude, altitude, mean, and minimum rainfall, moderately by latitude, which is strongly opposed by CV.

It is inferred that in most of clusters and periods (months, seasons and year), longitude has strong to moderate linkages with mean. However, these linkages are opposed mainly by CV. This finding suggests that mean rainfall increases when moving towards higher longitudes, and at the same time, CV decreases indicating less rainfall variations. This is true as rainfall in the area is lowest towards the western portion, and it increases towards the eastern portion, while CV has a gradient from west to east direction. In some cases, association of longitude and mean is opposed by latitude, which emphasizes that mean rainfall increases on moving towards the north. Moreover, this study justifies that rainfall is largely influenced by longitude, latitude, mean, SD and CV. Similarly, longitude and latitude have showed positive correlation with third harmonics of the seasonal and annual rainfall of Iran (Sabziparvar et al., 2015).

5. CONCLUSIONS

This study examined spatial patterns of monthly, seasonal and annual rainfall in northwest arid lands of India by delineating four clusters through HCA and investigating relative influence of eight geographical and statistical parameters on delineated clusters. The mean and medians of rainfall were the lowest for cluster-I located in the western portion, whereas, cluster-IV with the highest mean rainfall was situated towards the eastern portion. Skewness and kurtosis indicated presence of normality in rainfall clusters for all periods except for June and post-monsoon. CV suggested that minimum temporal variability (35-42%) for annual rainfall. Box-whisker plots confirmed normality in monsoon and annual rainfall. The mean monthly rainfall showed strong to moderate relationships with longitude, latitude, SD, maximum rainfall, and CV. Similarly, the mean seasonal and annual rainfall is correlated with longitude, latitude, altitude, SD, maximum rainfall, and minimum rainfall. Multicollinearity of the variables was evidenced from the results of Gleason-Staelin redundancy measure and Bartlett's test of sphericity, which suggested appropriateness of input variables to perform PCA. PCA resulted in 2-3 significant PCs explaining major variance for monthly (75.36-88.44% for June, 69.41-83.53% for July, 74.60-91.83% for August, and 73.70-86.58% for September), seasonal (63.62-90.39% for monsoon, 81.82-93.30% for post-monsoon, 75.74-88.60% for winter, and 64.31-77.77% for pre-monsoon) and annual (71.48-90.73%) rainfall. On unit circle plots of first two PCs, PC 1 was termed 'mean rainfall component'. In monthly and seasonal rainfall, close linkages of maximum rainfall and SD were observed. Also, longitude and mean values were opposed by CV. Outcome of this study emphasizes that rainfall increases on higher longitudes and latitudes, where rainfall variability decreases. Findings are useful for policy makers to formulate adequate guidelines for planning and management of unusual rainwater quantities in water-deficient lands.

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Table 1. Statistics of cluster-wise mean rainfall for monthly, seasonal and annual series

Period	Cluster	No. of Stations	Range (mm)	Mean (mm)	Standard Deviation (mm)	Coefficient of Variation (%)	Skewness	Kurtosis
June	I	7	0-262.6	**24.4**[a]	38.9	**160**[b]	4.6[#]	26.5[#]
	II	28	0.7-180.4	40.9	**31.6**[a]	**77**[a]	2.1[#]	6.4[#]
	III	18	1.2-146.4	39.8	32.1	81	1.6	2.6[#]
	IV	9	1.2-413.4	**58.5**[b]	**64.0**[b]	109	3.7[#]	18.0[#]
July	I	20	0.8-181.1	**73.5**[a]	**39.7**[a]	**54**[a]	0.8	0.2
	II	16	2.1-367.5	155.4	**89.2**[b]	57	0.6	-0.4
	III	11	9.5-566.2	124.4	80.5	**65**[b]	3.1[#]	16.0[#]
	IV	15	7.9-409.5	**155.5**[b]	88.3	57	1.1	1.1
August	I	11	3.1-626.3	127.9	**115.0**[b]	**90**[b]	2.5[#]	8.1[#]
	II	7	7.9-415.6	**136.4**[b]	97.4	71	1.0	0.6
	III	19	1.9-192.5	**63.1**[a]	**41.4**[a]	66	0.9	0.8
	IV	25	9.2-284.6	121.9	68.4	**56**[a]	0.6	-0.3
September	I	17	0.5-125.2	**28.9**[a]	**33.1**[a]	**115**[b]	1.5	1.3
	II	14	0-318.1	**64.2**[b]	**73.8**[b]	115	1.7	2.4[#]
	III	17	0.4-202.4	52.8	47.9	**91**[a]	1.3	1.3
	IV	14	0-210.2	42.7	41.9	98	1.9	4.9[#]
Monsoon	I	19	41-406.8	**192.3**[a]	**76.5**[a]	**40**[a]	0.5	0.3
	II	18	99.6-801.8	382.0	**170.4**[b]	**45**[b]	0.6	-0.3
	III	12	113.6-768.3	343.0	142.7	42	0.9	0.6
	IV	13	114.6-933.9	**389.7**[b]	155.3	40	1.2	2.4[#]
Post-Monsoon	I	24	0-71.2	**10.8**[a]	**15.4**[a]	**143**[a]	2.5[#]	6.9[#]
	II	10	0-136.3	17.6	29.6	168	2.4[#]	5.9[#]
	III	20	0-96.4	12.7	19.5	154	2.7[#]	7.5[#]
	IV	8	0-231.3	**18.9**[b]	**36.3**[b]	**192**[b]	4.3[#]	22.0[#]
Winter	I	26	0-39.4	**5.1**[a]	**7.0**[a]	**138**[b]	2.6[#]	9.4[#]
	II	6	0-87.7	14.1	**18.2**[b]	129	1.8	4.0[#]
	III	21	0-45	11.6	12.2	**105**[a]	1.2	0.5
	IV	9	0-72.8	**15.8**[b]	16.9	106	1.7	3.0[#]
Pre-Monsoon	I	20	0.7-62.6	16.0	**16.3**[a]	101	1.5	1.4
	II	8	0-133.3	**15.5**[a]	**27.8**[b]	**179**[b]	3.4[#]	11.6[#]
	III	21	0.5-116.3	**30.0**[b]	**27.8**[b]	93	1.7	2.5[#]
	IV	13	2.5-101.6	26.2	23.2	**89**[a]	1.7	2.7[#]
Annual	I	19	67.8-432.6	**231.8**[a]	**81.8**[a]	**35**[a]	0.3	-0.3
	II	18	128.3-845.2	418.6	**177.2**[b]	**42**[b]	0.5	-0.5
	III	10	182.7-822.1	390.4	144.9	37	0.7	0.3
	IV	15	157.8-961.7	**448.3**[b]	161.6	36	1.0	1.5

Note: Boldface indicate minimum/maximum among four clusters; a (or b) indicates minimum (or maximum) among four clusters of a given month/season; # indicates skewness/kurtosis outside limit of ±2.0.

Table 2. Values of correlation coefficient (R) depicting relationships of the mean rainfall with geographical and statistical parameters

Period	**Geographical Factors**			**Statistical Parameters**			
	Longitude	**Latitude**	**Altitude**	**SD**	**CV**	**Minimum Rainfall**	**Maximum Rainfall**
June	**0.73**[b]	0.00	**0.78**[b]	**0.71**[b]	-0.47	NA	**0.51**[c]
July	**0.57**[c]	-0.36	**0.63**[c]	**0.90**[a]	**-0.62**[c]	NA	**0.75**[b]
August	0.46	-0.46	**0.58**[c]	**0.72**[b]	-0.42	NA	**0.53**[c]
September	0.41	-0.44	0.45	**0.90**[a]	-0.47	NA	**0.80**[a]
Monsoon	**0.55**[c]	-0.38	**0.63**[c]	**0.85**[a]	-0.49	NA	**0.78**[b]
Post-monsoon	**0.51**[c]	-0.23	**0.54**[c]	**0.87**[a]	-0.33	NA	**0.68**[c]
Winter	**0.83**[a]	**0.78**[b]	0.46	**0.91**[a]	**-0.70**[b]	NA	**0.60**[c]
Pre-monsoon	**0.78**[b]	**0.70**[b]	0.47	**0.75**[b]	**-0.75**[b]	NA	**0.52**[c]
Annual	**0.63**[c]	-0.29	**0.67**[c]	**0.82**[a]	-0.48	**0.85**[a]	**0.77**[b]

Note: NA = not applicable; Boldface indicate $R>0.5$; a indicates very strong relationship ($R\geq0.8$); b indicates strong relationship ($0.8>R\geq0.7$); c indicates moderate relationship ($0.7>R\geq0.5$)

Table 3. Coordinates of two most significant principal components for monthly rainfall

Month	Variable	Cluster I		Cluster II		Cluster III		Cluster IV	
		PC 1	**PC 2**	**PC 1**	**PC 2**	**PC 1**	**PC 2**	**PC 1**	**PC 2**
June	Longitude	**0.8407**[a]	-0.2662	**-0.7835**[a]	-0.4288	**-0.8947**[a]	-0.0834	**0.8938**[a]	-0.2903
	Latitude	**-0.8682**[a]	0.1473	**-0.5954**[b]	0.3425	**0.8160**[a]	0.3831	**0.7725**[a]	**-0.6166**[b]
	Altitude	0.1621	**-0.5270**[b]	**-0.7621**[a]	-0.3879	**-0.8935**[a]	-0.1932	**0.8051**[a]	-0.0251
	Average	**0.9058**[a]	-0.3040	**-0.6366**[b]	**-0.5228**[b]	**-0.9376**[a]	0.0693	**0.7821**[a]	-0.4593
	SD	0.0603	**-0.9653**[a]	**-0.7666**[a]	0.3660	**-0.8151**[a]	**0.5404**[b]	**-0.5766**[b]	**-0.8034**[a]
	CV	**-0.8024**[a]	**-0.5565**[b]	-0.0331	**0.9834**[a]	**0.5683**[b]	**0.7270**[b]	**-0.9483**[a]	-0.2198
	Maximum	-0.3599	**-0.9008**[a]	**-0.7238**[b]	**0.6181**[b]	**-0.7564**[a]	**0.6183**[b]	**-0.5671**[b]	**-0.7822**[a]
July	Longitude	**0.6712**[b]	**-0.5609**[b]	**0.8518**[a]	0.4512	0.3783	-0.7347	**0.8773**[a]	-0.4165
	Latitude	0.1391	**-0.8219**[a]	0.4186	**0.7764**[a]	-0.4813	0.3006	**0.5562**[b]	-0.1785
	Altitude	**0.6004**[b]	**0.5778**[b]	**0.9130**[a]	0.2291	**0.6549**[b]	**-0.5049**[b]	**0.8917**[a]	-0.2102
	Average	**0.9624**[a]	0.1790	**0.7362**[b]	**-0.6206**[b]	0.1725	**-0.7267**[b]	**0.7831**[a]	**-0.5686**[b]
	SD	**0.7261**[b]	-0.2409	0.2956	**-0.8967**[a]	**-0.7982**[a]	**-0.5703**[b]	-0.4447	**-0.8696**[a]
	CV	**-0.8016**[a]	-0.4029	**-0.7913**[a]	-0.0654	**-0.8730**[a]	0.0289	**-0.9277**[a]	-0.2979
	Maximum	0.4486	-0.3932	0.4178	**-0.5945**[b]	**-0.7125**[b]	**-0.6297**[b]	**-0.5999**[b]	**-0.7238**[b]
August	Longitude	**0.8372**[a]	-0.4250	0.0758	**-0.9572**[a]	**0.8525**[a]	-0.1113	-0.4868	**0.7650**[a]
	Latitude	**-0.8906**[a]	-0.2456	**0.8999**[a]	-0.0001	**0.5534**[b]	0.4259	0.3416	**0.6539**[b]
	Altitude	0.3271	**-0.8694**[a]	0.2332	**-0.8973**[a]	0.3422	**-0.7533**[a]	**-0.8796**[a]	-0.0579
	Average	**0.8004**[a]	**-0.5787**[b]	**-0.7629**[a]	**-0.6411**[b]	0.2106	**-0.9056**[a]	**-0.9164**[a]	0.3240
	SD	-0.2925	**-0.9083**[a]	**-0.9444**[a]	-0.2993	**-0.6172**[b]	**-0.5043**[b]	**-0.8509**[a]	-0.3250
	CV	**-0.9838**[a]	-0.1499	**-0.7925**[a]	0.4506	**-0.8464**[a]	0.4273	0.2371	**-0.7605**[a]
	Maximum	**-0.6371**[b]	**-0.7400**[b]	**-0.9731**[a]	0.1365	**-0.8592**[a]	-0.4168	**-0.8269**[a]	-0.3613
September	Longitude	0.2568	**-0.8855**[a]	**0.6264**[b]	**0.7424**[b]	**0.9035**[a]	-0.1432	**0.8021**[a]	0.0973
	Latitude	**0.6462**[b]	-0.3832	**0.8573**[a]	0.3119	**-0.7596**[a]	0.1326	**-0.8291**[a]	-0.3528
	Altitude	-0.2974	-0.4995	0.2288	**0.9475**[a]	**0.8360**[a]	-0.2558	**0.8940**[a]	0.2252
	Average	**-0.8647**[a]	-0.4691	**-0.6109**[b]	**0.7134**[b]	**0.9453**[a]	0.1413	**0.9444**[a]	-0.0516
	SD	**-0.9557**[a]	-0.1337	**-0.8565**[a]	**0.5012**[b]	**0.6869**[b]	**0.6828**[b]	**0.8288**[a]	-0.4858
	CV	-0.0169	**0.8545**[a]	**-0.6857**[b]	-0.3276	**-0.7061**[b]	**0.6125**[b]	**-0.8178**[a]	-0.4241
	Maximum	**-0.8521**[a]	0.2258	**-0.8752**[a]	0.3526	0.2998	**0.9135**[a]	**0.7294**[b]	**-0.6408**[b]

Note: PC = Principal Component; SD = Standard Deviation; CV = Coefficient of Variation; Boldface indicate significant principal components; a indicates strongly significant and b indicates moderately significant

Table 4. Coordinates of two most significant principal components for seasonal and annual rainfall

Season/Year	Variable	Cluster I		Cluster II		Cluster III		Cluster IV	
		PC 1	**PC 2**	**PC 1**	**PC 2**	**PC 1**	**PC 2**	**PC 1**	**PC 2**
Monsoon	Longitude	**-0.7826[a]**	-0.0182	**-0.8365[a]**	0.4552	-0.3288	**-0.6995[b]**	**-0.9717[a]**	0.0317
	Latitude	-0.3943	0.3956	-0.2993	**0.9198[a]**	**0.7370[b]**	-0.3046	**-0.6259[b]**	-0.4375
	Altitude	-0.4710	**-0.6867[b]**	**-0.8951[a]**	0.2437	**-0.7857[a]**	0.1252	**-0.8715[a]**	0.0957
	Average	**-0.6354[b]**	**-0.6886[b]**	**-0.8496[a]**	-0.4710	**-0.7051[b]**	**-0.5517[b]**	**-0.9534[a]**	0.2118
	SD	**0.5938[b]**	**-0.6840[b]**	-0.4077	**-0.8927[a]**	**-0.9164[a]**	0.1422	-0.2035	**0.9503[a]**
	CV	**0.9572[a]**	-0.1254	**0.7778[a]**	**-0.5371[b]**	-0.4127	**0.6554[b]**	**0.7888[a]**	**0.5424[b]**
	Maximum	**-0.6743[b]**	-0.4444	**-0.9077[a]**	-0.0922	0.0561	**-0.6230[b]**	**-0.7574[a]**	0.3125
Post-Monsoon	Longitude	**-0.8577[a]**	-0.4218	-0.3597	**0.9255[a]**	**0.9216[a]**	0.0097	**-0.9697[a]**	-0.1222
	Latitude	0.0551	**-0.8312[a]**	-0.1298	**0.9219[a]**	**-0.8058[a]**	-0.0003	**0.8481[a]**	0.1557
	Altitude	**-0.7450[b]**	**-0.5631[b]**	**-0.5976[b]**	**0.6639[b]**	**0.9148[a]**	-0.1440	**-0.9735[a]**	-0.2088
	Average	**-0.9474[a]**	0.1734	**-0.7515[a]**	-0.4048	**0.8793[a]**	0.1304	**-0.9643[a]**	0.0036
	SD	**-0.8133[a]**	**0.5342[b]**	**-0.9284[a]**	-0.3629	0.4820	**0.8329[a]**	**-0.8084[a]**	**0.5625[b]**
	CV	**0.5923[b]**	0.4561	**-0.8114[a]**	-0.2077	**-0.7130[b]**	**0.6067[b]**	**0.7273[b]**	**0.6573[b]**
	Maximum	**-0.6499[b]**	**0.6260[b]**	**-0.9638[a]**	-0.0413	0.0413	**0.9459[a]**	**-0.6040[b]**	**0.7843[a]**
Winter	Longitude	**0.9173[a]**	-0.0794	**0.9774[a]**	-0.0224	-0.0026	**-0.9290[a]**	**-0.9454[a]**	0.0368
	Latitude	-0.0145	**0.7175[b]**	**0.8881[a]**	-0.0939	**0.8635[a]**	0.4149	0.0570	**0.6358[b]**
	Altitude	**0.8187[a]**	0.1597	**0.9411[a]**	-0.2703	**-0.5731[b]**	**-0.8006[a]**	**-0.7092[b]**	**-0.5239[b]**
	Average	**0.9243[a]**	0.1896	**0.9374[a]**	0.2895	**0.8794[a]**	-0.3949	**-0.9244[a]**	0.0649
	SD	**0.5459[b]**	**-0.7788[a]**	0.4667	**0.8194[a]**	**0.7015[b]**	-0.4454	-0.4481	**-0.7397[b]**
	CV	-0.3919	**-0.8545[a]**	**-0.7929[a]**	0.4915	**-0.6843[b]**	0.2039	**0.8093[a]**	**-0.5666[b]**
	Maximum	0.1420	**-0.9328[a]**	0.1100	**0.8692[a]**	**0.7091[b]**	-0.0286	0.2442	**-0.7611[a]**
Pre-Monsoon	Longitude	**-0.7201[b]**	-0.4886	**0.7722[a]**	-0.1991	**0.5536[b]**	-0.1590	**-0.8105[a]**	-0.2309
	Latitude	-0.0650	0.0041	**0.8222[a]**	-0.2707	**-0.6040[b]**	**-0.5628[b]**	**0.9201[a]**	-0.1182
	Altitude	**-0.7208[b]**	-0.2853	**0.5827[b]**	-0.1866	**0.7616[a]**	0.2920	**-0.9294[a]**	-0.0046
	Average	**-0.9167[a]**	0.0789	**0.9377[a]**	-0.0173	0.2005	**-0.8768[a]**	0.3142	**-0.9133[a]**
	SD	**-0.7805[a]**	**0.5821[b]**	**0.7525[a]**	**0.6002[b]**	**0.8179[a]**	-0.3793	-0.2355	**-0.8866[a]**
	CV	**0.6275[b]**	**0.6159[b]**	**-0.8269[a]**	0.3099	**0.6009[b]**	0.4808	**-0.6251[b]**	0.4728
	Maximum	**-0.5142[b]**	**0.8111[b]**	0.3368	**0.9084[a]**	**0.6562[b]**	-0.4224	**-0.6465[b]**	-0.4503
Annual	Longitude	**0.8977[a]**	0.0933	**-0.8526[a]**	0.4239	-0.0512	**-0.9165[a]**	**0.9690[a]**	-0.0333
	Latitude	**0.5356[b]**	-0.1160	-0.3140	**0.9093[a]**	**-0.6345[b]**	0.1320	**0.6319[b]**	**0.5449[b]**
	Altitude	0.4389	0.2788	**-0.8948[a]**	0.2181	**0.5438[b]**	-0.2769	**0.8493[a]**	-0.2091
	Average	**0.8331[a]**	0.4967	**-0.8526[a]**	-0.4913	-0.2717	**-0.8868[a]**	**0.9648[a]**	-0.1619
	SD	-0.2310	**0.9389[a]**	-0.4392	**-0.8793[a]**	**0.8901[a]**	-0.3158	0.1589	**-0.9434[a]**
	CV	**-0.8712[a]**	0.4210	**0.8004[a]**	**-0.5114[b]**	**0.9212[a]**	0.1844	**-0.7563[a]**	**-0.5982[b]**
	Minimum	**0.8775[a]**	0.2870	**-0.9403[a]**	-0.0206	**-0.7276[b]**	**-0.5187[b]**	**0.8605[a]**	-0.2914
	Maximum	-0.2387	**0.9470[a]**	**-0.6255[b]**	**-0.6826[b]**	**0.6202[b]**	**-0.5155[b]**	0.0350	**-0.8563[a]**

Note: PC = Principal Component; SD = Standard Deviation; CV = Coefficient of Variation; Boldface indicate significant principal components; a indicates strongly significant and b indicates moderately significant

Figure Captions

Fig. 1. Map showing location of study area along with rainfall stations

Fig. 2. Stations classified into four groups for monthly (a-d), seasonal (e-h) and annual (i) rainfall

Fig. 3. Box-whisker plots of cluster-wise rainfall for (a) monthly, (b) seasonal and (c) monsoon/annual rainfall

Fig. 4. Unit circle plots of two significant principal components showing association of 7 parameters with mean monthly rainfall (Long – Longitude, Lat – Latitude, Alt – Altitude, Avg – Average, SD – Standard deviation, CV – Coefficient of variation, Max – Maximum)

Fig. 5. Unit circle plots of two significant principal components showing association of 8 parameters with mean seasonal rainfall

Fig. 6. Unit circle plots of two significant principal components showing association of 8 parameters with mean monsoon and annual rainfall

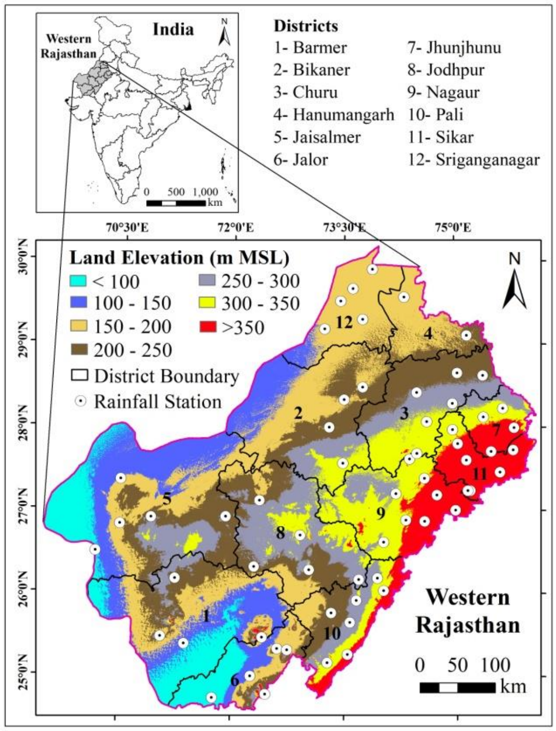

India
Western Rajasthan
0 500 1,000 km
Districts
1- Barmer
2- Bikaner
3- Churu
4- Hanumangarh
5- Jaisalmer
6- Jalor
7- Jhunjhunu
8- Jodhpur
9- Nagaur
10- Pali
11- Sikar
12- Sriganganagar
70°30'E
72°0'E
73°30'E
75°0'E
30°0'N
29°0'N
28°0'N
27°0'N
26°0'N
25°0'N
Land Elevation (m MSL)
< 100
100 - 150
150 - 200
200 - 250
250 - 300
300 - 350
>350
District Boundary
Rainfall Station
N
Western Rajasthan
0 50 100 km

Figure 1

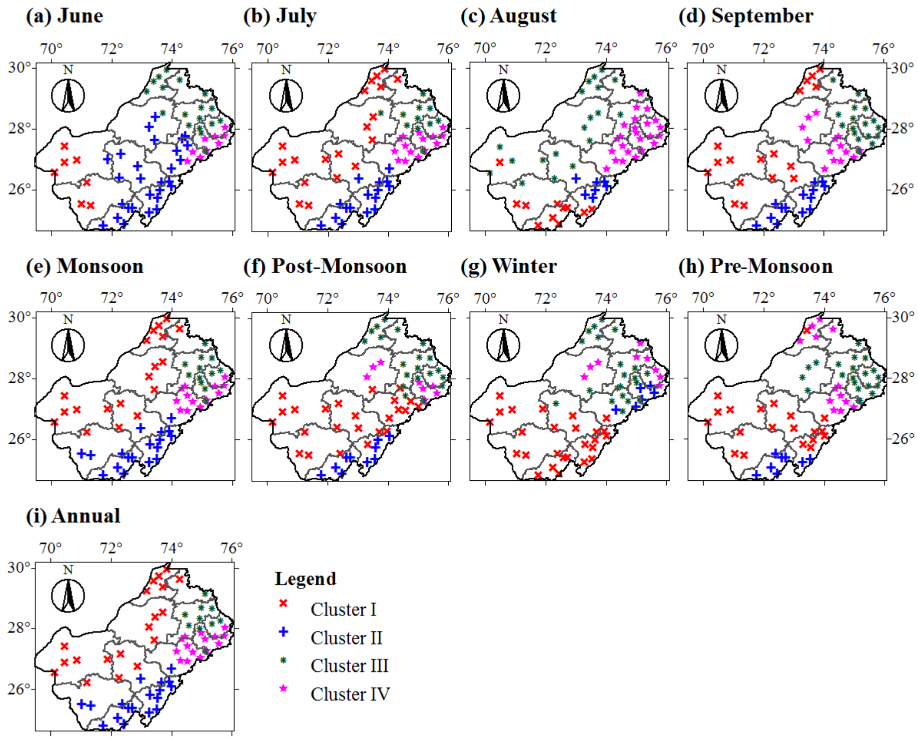
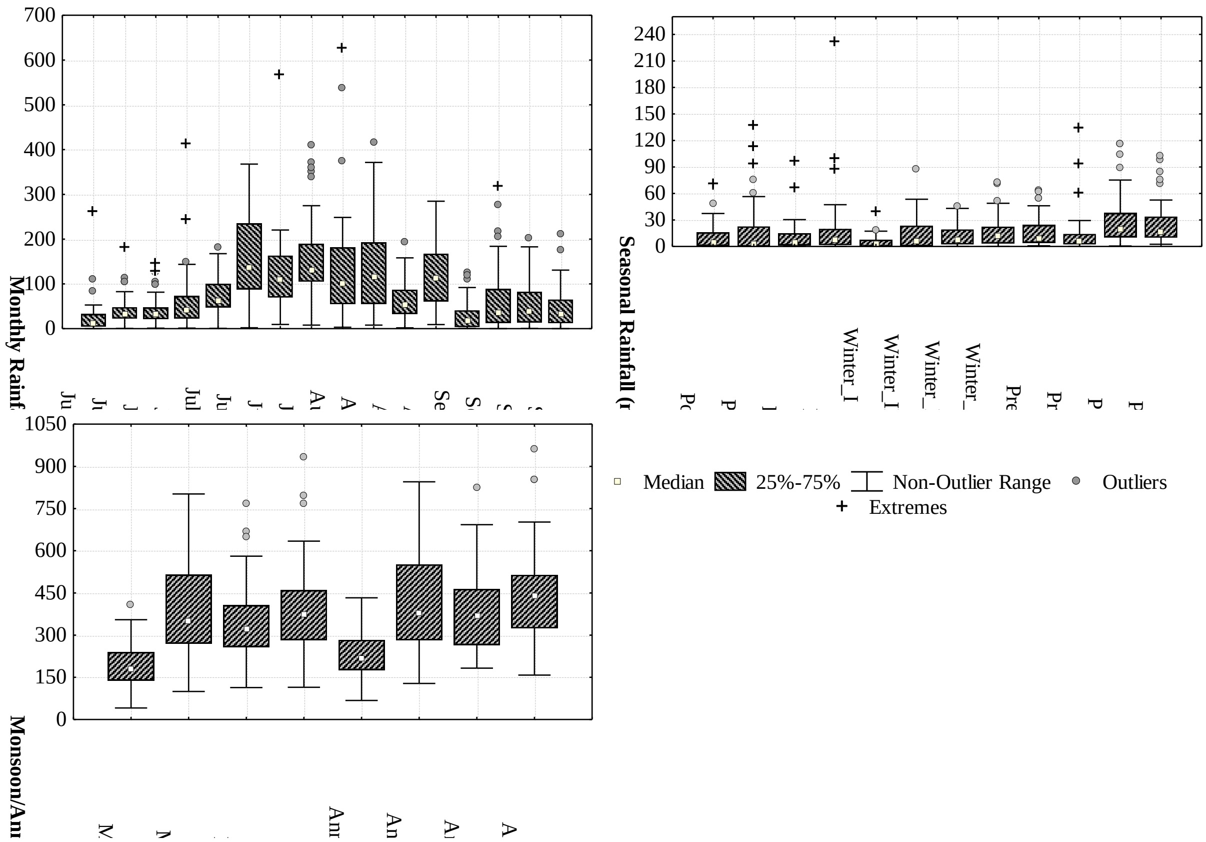

(a) June
(b) July
(c) August
(d) September
(e) Monsoon
(f) Post-Monsoon
(g) Winter
(h) Pre-Monsoon
(i) Annual
70°
72°
74°
76°
30°
28°
26°
N
Legend
Cluster I
Cluster II
Cluster III
Cluster IV

Figure 2



Monthly Rainf
Seasonal Rainfall (r
Monsoon/Anı
Median
25%-75%
Non-Outlier Range
Outliers
Extremes

Figure 3

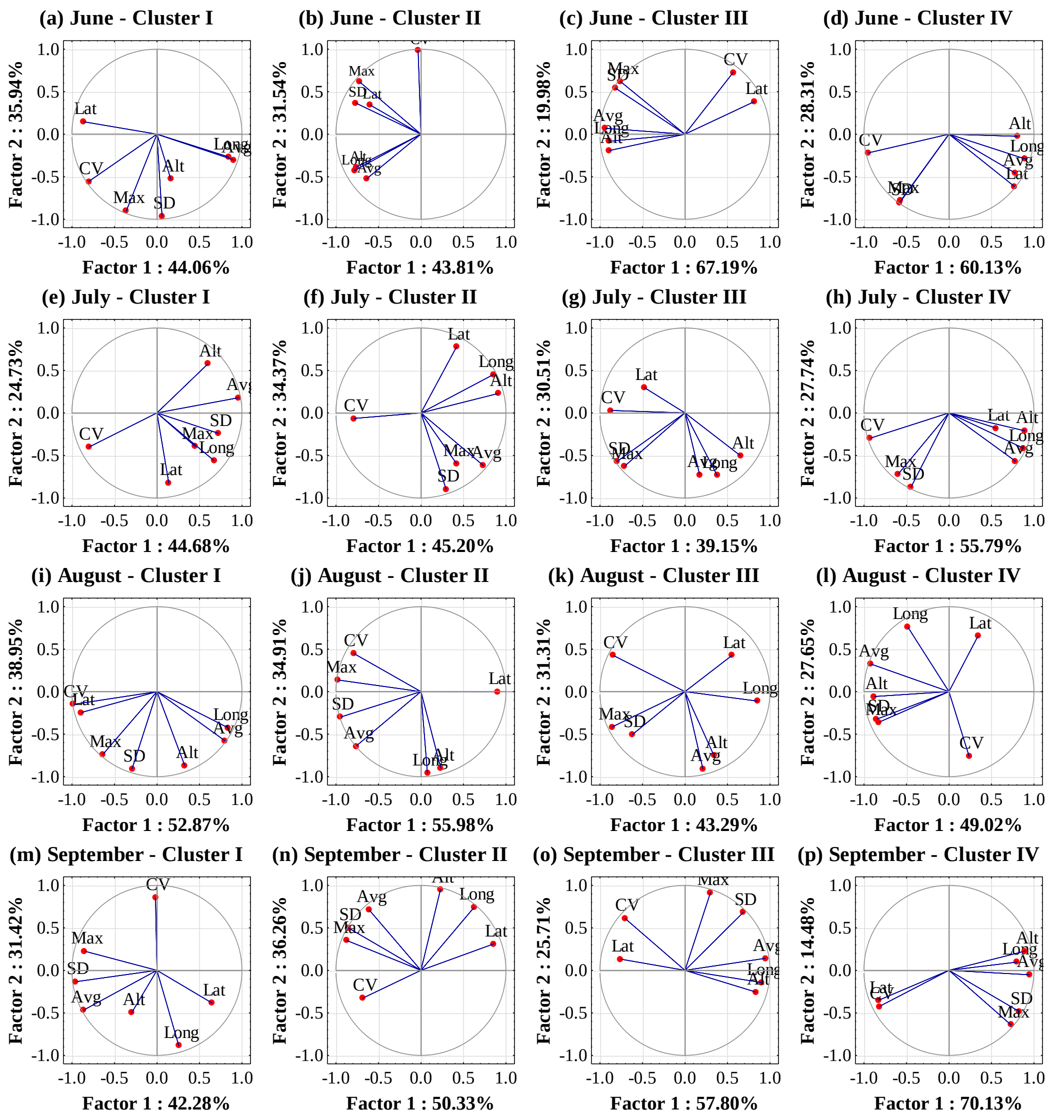
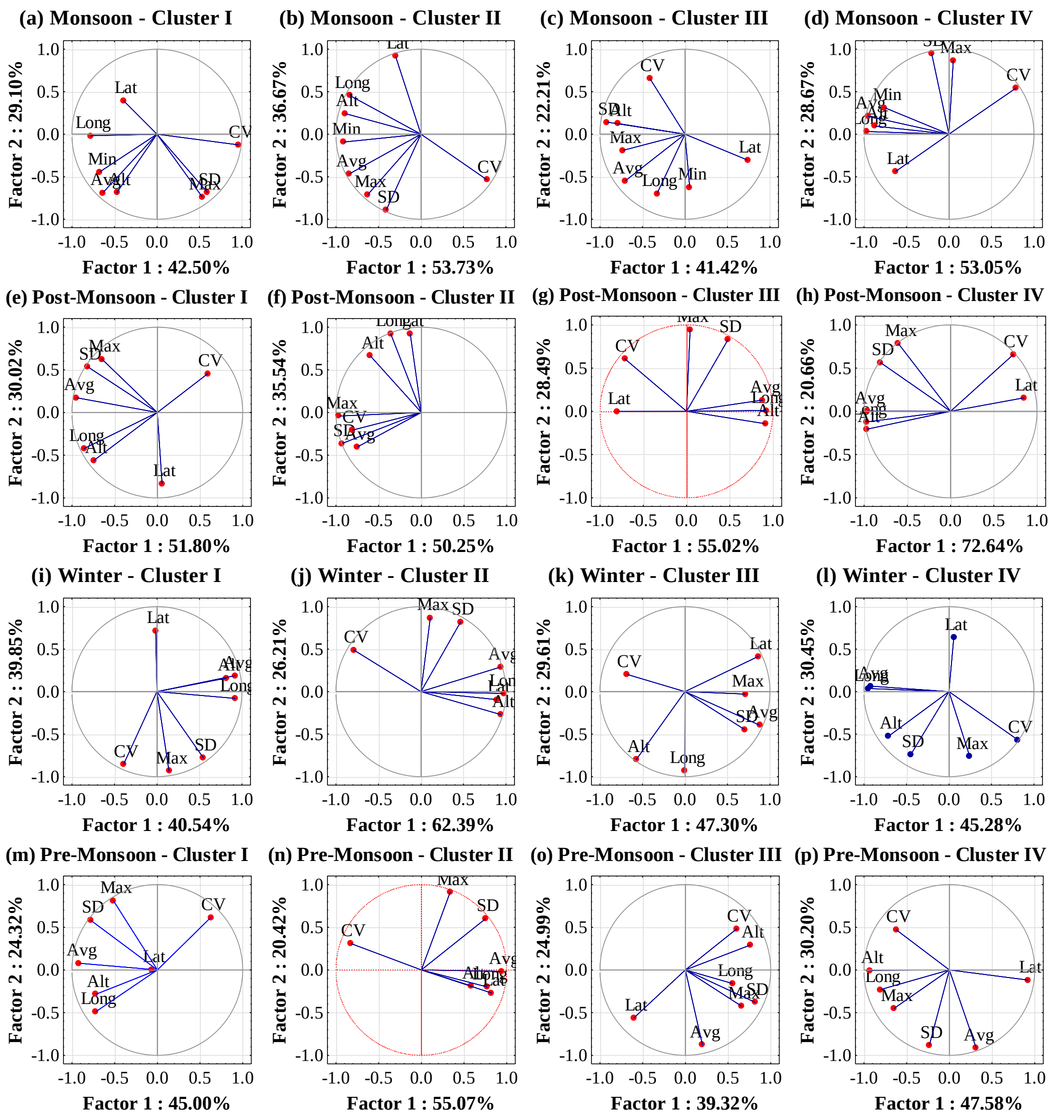

(a) June - Cluster I
Factor 2 : 35.94%
Factor 1 : 44.06%
(b) June - Cluster II
Factor 2 : 31.54%
Factor 1 : 43.81%
(c) June - Cluster III
Factor 2 : 19.98%
Factor 1 : 67.19%
(d) June - Cluster IV
Factor 2 : 28.31%
Factor 1 : 60.13%
(e) July - Cluster I
Factor 2 : 24.73%
Factor 1 : 44.68%
(f) July - Cluster II
Factor 2 : 34.37%
Factor 1 : 45.20%
(g) July - Cluster III
Factor 2 : 30.51%
Factor 1 : 39.15%
(h) July - Cluster IV
Factor 2 : 27.74%
Factor 1 : 55.79%
(i) August - Cluster I
Factor 2 : 38.95%
Factor 1 : 52.87%
(j) August - Cluster II
Factor 2 : 34.91%
Factor 1 : 55.98%
(k) August - Cluster III
Factor 2 : 31.31%
Factor 1 : 43.29%
(l) August - Cluster IV
Factor 2 : 27.65%
Factor 1 : 49.02%
(m) September - Cluster I
Factor 2 : 31.42%
Factor 1 : 42.28%
(n) September - Cluster II
Factor 2 : 36.26%
Factor 1 : 50.33%
(o) September - Cluster III
Factor 2 : 25.71%
Factor 1 : 57.80%
(p) September - Cluster IV
Factor 2 : 14.48%
Factor 1 : 70.13%

Figure 4



(a) Monsoon - Cluster I
(b) Monsoon - Cluster II
(c) Monsoon - Cluster III
(d) Monsoon - Cluster IV
(e) Post-Monsoon - Cluster I
(f) Post-Monsoon - Cluster II
(g) Post-Monsoon - Cluster III
(h) Post-Monsoon - Cluster IV
(i) Winter - Cluster I
(j) Winter - Cluster II
(k) Winter - Cluster III
(l) Winter - Cluster IV
(m) Pre-Monsoon - Cluster I
(n) Pre-Monsoon - Cluster II
(o) Pre-Monsoon - Cluster III
(p) Pre-Monsoon - Cluster IV
Factor 1 : 42.50%
Factor 2 : 29.10%
Factor 1 : 53.73%
Factor 2 : 36.67%
Factor 1 : 41.42%
Factor 2 : 22.21%
Factor 1 : 53.05%
Factor 2 : 28.67%
Factor 1 : 51.80%
Factor 2 : 30.02%
Factor 1 : 50.25%
Factor 2 : 35.54%
Factor 1 : 55.02%
Factor 2 : 28.49%
Factor 1 : 72.64%
Factor 2 : 20.66%
Factor 1 : 40.54%
Factor 2 : 39.85%
Factor 1 : 62.39%
Factor 2 : 26.21%
Factor 1 : 47.30%
Factor 2 : 29.61%
Factor 1 : 45.28%
Factor 2 : 30.45%
Factor 1 : 45.00%
Factor 2 : 24.32%
Factor 1 : 55.07%
Factor 2 : 20.42%
Factor 1 : 39.32%
Factor 2 : 24.99%
Factor 1 : 47.58%
Factor 2 : 30.20%

Figure 5

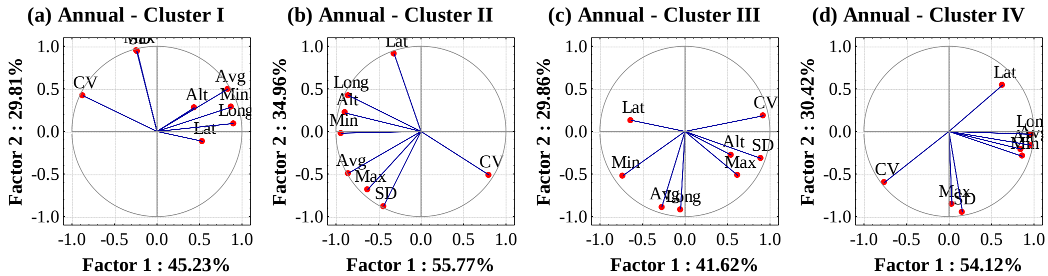

(a) Annual - Cluster I
(b) Annual - Cluster II
(c) Annual - Cluster III
(d) Annual - Cluster IV
Factor 1 : 45.23%
Factor 2 : 29.81%
Factor 1 : 55.77%
Factor 2 : 34.96%
Factor 1 : 41.62%
Factor 2 : 29.86%
Factor 1 : 54.12%
Factor 2 : 30.42%

Figure 6