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Regional precipitation climates of Iran

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Abstract
Rainfall in Iran is complex, with unpredictable fluctuations from year to year and from region to region. At-site frequency analysis is inadequate for regional planning. Thus, it is important to determine regional rainfall frequencies. Hierarchical cluster analysis and L-moments regional frequency analysis were used in this study to find homogeneous rainfall groups and regional rainfall frequency distributions. The study showed eight homogeneous rainfall regions within Iran, which correspond with areas with differing geography and climate. A regional homogeneity measure, H_1, showed that a 3-parameter log-normal distribution describes the overall distribution of rainfall within Iran, but because of substantial variations in precipitation patterns within the country, the distribution is not applicable for individual regions. Z-statistics, which are based on L-moments, were used to select the distribution that best fitted rainfall records in each homogeneous region.

Key Words
Rainfall frequency analysis, cluster analysis, Ward's method, L-moments, Iran

Introduction
Rainfall frequency analysis is important for atmospheric research, flood estimation models and hydrologic design, planning and management. Rainfall variation within Iran is complex, with unpredictable rainfall fluctuations from year to year and from region to region. To simplify hydrologic calculations and reduce masses of observations and variables for frequency analysis, meteorologists and hydrologists have tried to group spatial and temporal patterns to define homogenous rainfall regions within Iran.

Several methods are commonly used for the regionalization of hydrologic phenomena such as rainfall, streamflow and other components of the water cycle, to determine if an area has hydrologically homogeneous regions. Multivariate techniques can be powerful tools for classifying meteorological data such as rainfall. Principle component analysis, factor analysis and different types of cluster analysis have been used to classify daily rainfall patterns and their relationship to atmospheric circulation (Romero *et al.*, 1999), flood and drought years (Singh, 1999), and streamflow drought (Stahl and Demuth, 1999). Gottschalk (1985) suggested the application of multivariate methods to classify hydrologic events on a national scale. Guttman (1993) applied L-moments and cluster analysis to determine regional rainfall climates within conterminous United States; he defined 104 homogeneous precipitation regions there.

One of the first efforts on rainfall regionalization in Iran was carried out by Vaziri (1997), who divided Iran into seven groups based on rainfall intensity-duration curves. Recently, Masoodian (1998) and Domroes *et al.* (1998) have applied multivariate principle component techniques to classify rainfall patterns in Iran; they found six and five precipitation groups across Iran, respectively.

This study examines rainfall frequency distributions in Iran to find regional patterns. Because of the variation of rainfall pattern, we first classify rainfall spatial groups in Iran through cluster analysis, and then apply L-moment procedures for regional frequency analysis within the homogeneous areas defined by the cluster analysis.

Rainfall data

The annual and monthly rainfall of 28 main cities of the provinces of Iran are used as the data set to determine Iran's rainfall spatial patterns. The World Meteorological Organization (WMO) suggests using 30-year rainfall periods for rainfall analysis, but when analysing variations over time, data for shorter periods (10 or 20 years) can also be used (Moron, 1997; Salinger and Mullan, 1999; Ramos, 2001). The data set of this study contains annual and monthly rainfalls with record lengths ranging from 13 to 30 years. Masoodian (1998) showed that the average annual rainfall of Iran is 260 mm, with a maximum rainfall along the margin of the Caspian Sea in the north of Iran: the main city of Guilan province, Rasht, is representative of this region. Figure 1 shows the spatial distribution of the stations in Iran used in this study. The boundary of each province is also illustrated.

Cluster analysis

Cluster analysis for hydrologic regionalization involves the grouping of observations or variables into clusters, with each cluster containing observations or variables with highly similar hydrologic characteristics, such as geographical, physical, statistical or stochastic features. Mosley (1981) used hierarchical clusters for the rivers in New Zealand and Tasker (1982) compared methods of defining homogeneous regions, including

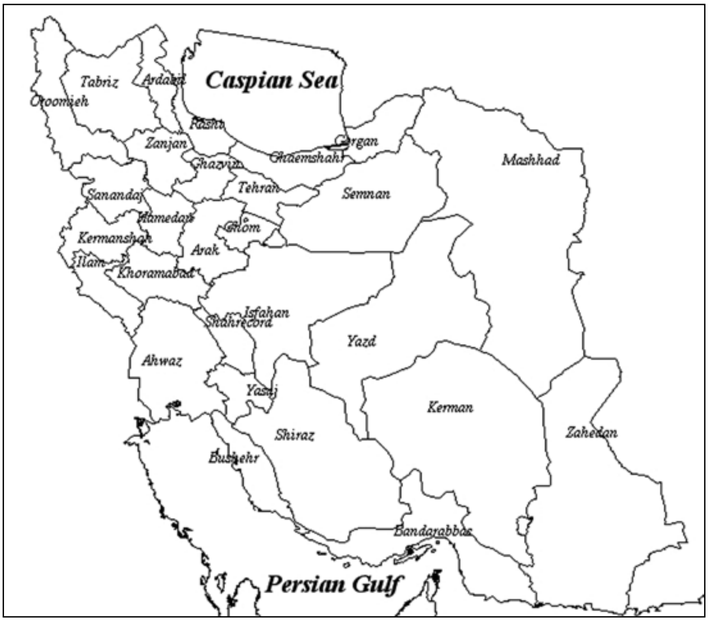

Figure 1 – Provinces of Iran and the location of the selected rainfall stations in each province.

cluster analysis, with a complete linkage algorithm. Acreman (1985) and Acreman and Sinclair (1986) concluded that cluster analysis is useful for explaining observed variation in their data. Gottschalk (1985) applied cluster and principal component analysis to data from Sweden and found that cluster analysis is suitable to use on a national scale for a country with heterogeneous hydrological regimes. Nathan and McMahon (1990) used hierarchical cluster analysis to predict low-flow characteristics in southeastern Australia. They found that Ward's method, with a dissimilarity measure based on the squared Euclidean distance, is the best method for classification.

The commonly used dissimilarity Euclidean distance measure is written as follows:

$$d_{rs}^2 = \sum_{j=1}^{p} (x_{rj} - x_{sj})^2 \qquad (1)$$

where *rth* and *sth* rows of the data matrix, **X,** are denoted by (x_{r1}, x_{r2}, …,x_{rp}) and (x_{s1}, x_{s2}, …, x_{sp}) respectively. These two rows correspond to the observations on two objects for all *P* variables. The quantity d_{rs}^2 is referred to as the squared Euclidean distance (Jobson, 1992). The Euclidean distance of dissimilarity is then used in the cluster techniques.

In this study, we apply the hierarchical cluster technique described by Kaufman and Rousseuw (1990). Several methods have been proposed for hierarchical cluster analysis, including single, average and complete linkage, and Ward's minimum variance method; both average linkage and Ward's method are widely used (Milligan, 1980; Jackson and Weinand, 1995; Ramos, 2001). Nathan and McMahon (1990), Masoodian (1998) and Domroes *et al.* (1998) indicate that Ward's method gives better results, so we have used Ward's method for cluster analysis of rainfall data in this study.

Ward's method calculates the distance between two clusters as the sum of squares between two clusters, added up over all variables. At each generation, the sum of squares is minimized. If C_K and C_L are two rainfall clusters that merged to form the cluster C_M, the distance between the new cluster and another cluster C_J is:

$$d_{J.M} = \frac{((n_J + n_K))d_{jk} + (n_J + n_L)d_{JL} - n_J d_{KL})}{n_J + n_M} \qquad (2)$$

where n_J, n_K, n_L and n_M are the number of the rainfall stations in clusters *J*, *K*, *L* and *M*, respectively, and d_{JK}, d_{JL} and d_{KL} represent the distances between the rainfall observations in the clusters *J* and *K*, *J* and *L*, and *K* and *L*, respectively. To select a suitable number of rainfall clusters, two statistics are used: pseudo *F* and t^2 statistics (SAS,1999) (not shown here).

Based on the Ward's method and using the annual and monthly rainfall (1+12 variables) of the selected rainfall stations, eight clusters can be found, based on the greatest similarity (smallest dissimilarity):

1) Yazd, Zahedan, Isfahan, Semnan, Kerman and Ghom;
2) Arak, Shahrecord, Ghazvin, Tehran, Mashhad and Hameda;
3) Oroomieh, Ardabil, Zanjan and Tabriz;
4) Ahwaz, Bushehr, Shiraz, and with a small difference, Bandarabbas;
5) Kermanshah, Sanandaj and Khoramabad;
6) Ghaemshahr and Gorgan;
7) Ilam and Yasuj;
8) Rasht.

These eight clusters cover 90 per cent of the rainfall variance within Iran. The first group is the largest: it includes stations in arid and semi-arid regions in the centre of Iran. The second group is stations located in the highland margins of regions in the first group. Another group includes stations in the northwestern cold region – Oroomieh, Ardabil, Zanjan and Tabriz stations (called

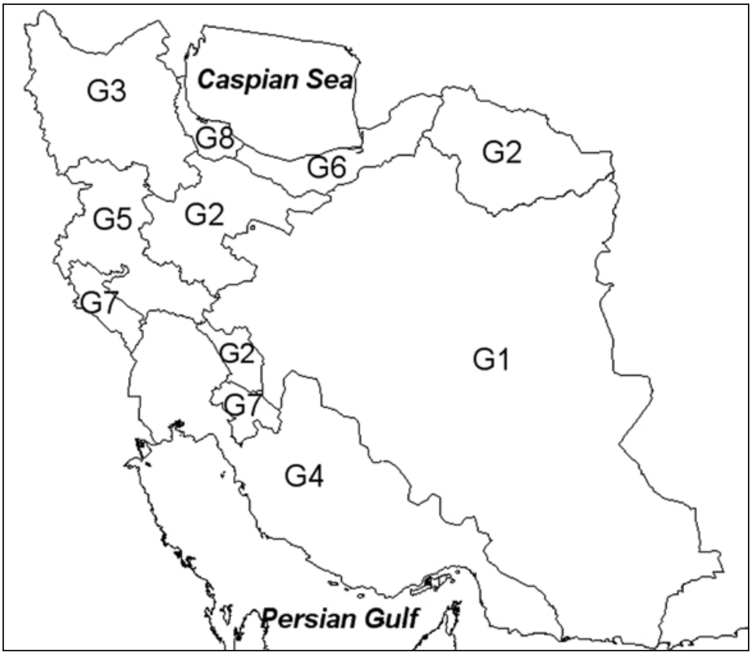

Figure 2 – Spatial distribution of rainfall groups over Iran.

the 'Azari' group by Masoodian (1998)). The fourth group includes stations along the margin of the Persian Gulf in the south of Iran, while the sixth and the eighth groups are areas located along the margin of the Caspian Sea. The major difference between the sixth and eighth groups in the north of Iran is the amount of rainfall, which decreases from west (Rasht) to east (Ghaemshahr and Gorgan). The fifth and seventh groups are regions in the Zagros Mountains, with the amount of rainfall higher in the seventh group. The geographic distribution of the eight groups is shown in Figure 2. Once these cluster-based groups were distinguished, we applied L-moments to check the homogeneity of each group and to find the regional frequency distribution for each one.

Regional frequency analysis

Hydrologists have proposed several methods for regional frequency analysis. Perhaps the most popular method is L-moments. Greenwood *et al.* (1979) introduced the concept of probability-weighted moments. Hosking (1990) defined L-moments as equivalent to probability-weighted moments, as L-moments can be expressed by linear combinations of probability-weighted moments (Rao and Hamed, 1997). Hosking and Wallis (1993) extended the use of L-moments and developed useful statistics for regional frequency analysis to measure discordancy, regional homogeneity and goodness of fit.

Homogeneity and discordancy test

Hosking and Wallis (1993) derived two statistics to test the homogeneity of a region. The first statistic (H_i, i=1, 2 and 3) is used as a measure of homogeneity. A region is homogenous if H_i is less than 1, possibly heterogeneous if H_i is between 1 and 2, and definitely heterogeneous if H_i is greater than 2 (Hosking and Wallis, 1993). In this study, we use H_1 to measure regional homogeneity, as suggested by Rao and Hamed (1997). H_1 is more effective in determining homogenous regions than H_2 and H_3. H_1 is based on L-Cv only. Using the FORTRAN computer program developed by Hosking (1991), the homogeneity measure for all 28 stations is H_1=8.43. Based on this statistic, rainfall across Iran is definitely heterogeneous, because of large geographic and climatic differences within the country.

The second statistic is used as a measure of discordancy. If the discordancy measure (D) is larger than 3, the site is considered to be discordant. The results of discordancy analysis for all the stations are presented in Table 1. Only Yazd station has a value of (D) greater than 3. We then calculated the homogeneity measure for each group derived from the cluster analysis to see if these groups are homogenous. Table 2 summarises the homogeneity measures of each group.

Table 1 – Descriptive and L-moments statistics of the rainfall at selected stations

No.	Sample size	Station name	MEAN	STDEV	L-Cv	L-Cs	L-Ck	D
1	30	Ahwaz	213.30	86.30	0.18	-0.13	0.07	0.56
2	30	Arak	345.00	92.78	0.15	-0.28	-0.09	1.72
3	23	Ardabil	309.00	88.02	0.15	-0.13	-0.07	0.91
4	30	Bandarabbas	192.00	121.80	0.31	0.04	0.03	2.75
5	30	Bushehr	275.60	118.81	0.22	0.04	0.05	0.52
6	30	Ghaemshahr	752.30	116.68	0.08	-0.28	-0.01	1.33
7	25	Gorgan	612.10	102.83	0.09	-0.39	-0.01	0.78
8	30	Ghazvin	315.90	89.48	0.15	-0.08	-0.02	0.47
9	23	Hamedan	316.20	76.57	0.13	-0.20	-0.06	0.52
10	30	Isfahan	121.40	40.10	0.17	-0.23	-0.03	1.47
11	13	Ilam	627.90	170.69	0.14	-0.44	-0.10	0.42
12	30	Oroomieh	349.30	98.40	0.16	0.0	0.02	0.99
13	13	Ghom	149.00	47.10	0.17	-0.41	-0.26	1.72
14	30	Zahedan	94.80	40.14	0.26	0.11	-0.04	1.92
15	30	Zanjan	317.60	72.60	0.13	-0.28	0.01	0.56
16	30	Yazd	62.10	27.88	0.67	0.75	0.59	3.32
17	13	Yasuj	822.90	183.02	0.11	-0.58	-0.15	0.32
18	30	Tehran	229.20	63.92	0.14	-0.18	-0.04	0.27
19	30	Tabriz	293.30	68.05	0.14	-0.17	-0.06	0.44
20	30	Shiraz	344.70	99.69	0.16	-0.25	-0.03	0.92
21	30	Shahrecord	319.00	86.57	0.14	-0.16	-0.08	0.65
22	30	Semnan	139.90	54.22	0.20	-0.06	0.03	0.16
23	30	Sanandaj	471.00	118.78	0.13	-0.28	0.12	2.00
24	30	Rasht	1353.00	279.35	0.11	-0.16	-0.03	1.07
25	30	Mashhad	257.50	77.41	0.16	-0.13	-0.06	0.48
26	30	Khoramabad	515.10	125.61	0.12	-0.33	0.06	1.50
27	30	Kermanshah	450.80	120.40	0.14	-0.20	-0.02	0.15
28	25	Kerman	158.90	50.18	0.17	-0.13	0.02	0.07

STDEV: Standard Deviation; **L-Cv:** Measure of Variation; **L-Cs:** Measure of skewness;
L-Ck: Measure of Kurtosis; **D:** Discordancy measure

Table 2 – Homogeneity measure (H_1) of the derived groups (H^{1*} shows homogeneity measure after removing discordant station)

	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
H_1	1.08	-1.65	-0.9	2.47	-0.96	-0.52	-0.53
H_1*	0.06	–	–	0.55	–	–	–
Discordant station	Yazd	–	–	Bandarabbas	–	–	–

As group 8 has only one station, we could not calculate H statistics for this group. There are two discordant stations: Yazd in group 1 and Bandarabbas in group 4. Yazd lies the middle of the central arid zone of Iran and Bandarabbas is a harbor city next to the Persian Gulf. Their rainfall patterns are thus very different from patterns of other stations in their groups. If we remove these stations from the groups and recalculate H_1 statistics, groups 1 and 4 are homogeneous. Except for groups 1 and 4, the negative values of H_1 in other groups indicate less heterogeneity (more homogeneity) of the group. All stations in group 4 are affected by sea moisture, but Ahwaz and Shiraz stations are far from sea, in the highlands of the mountainous area. Similarly, for the stations in group 1, Yazd station is located in the centre of the arid region of Iran, while the other stations are within the semi-arid margin of the central arid zone.

Quantile estimation and goodness-of-fit-tests

Quantile estimation is the main goal of hydrologic frequency analysis. Quantiles are estimated by applying a frequency distribution function. An easy way to find the frequency distribution is the moment ratio diagram. L-moment diagrams provide a visual comparison of the sample estimates with the population values of L-moments (Stedinger *et al.*, 1993) and are always preferable to product moment ratio diagrams for a goodness-of-fit test (Vogel and Fennessey, 1993). Figure 3 shows moment ratio diagrams for all selected stations and three of the most common 3-parameter distributions, namely, Generalized Extreme Value, Generalized Logistic, 3-parameter Log Normal and Pearson type 3 distributions. The figure was drawn using the FREQ program in MATLAB, developed by Rao and Hamed (2000). The discordant Yazd station shows different conditions, according to the LC_v-LC_s and LC_s-LC_k diagrams: it lies in the middle of Iran's arid region, where rainfall variation is significantly higher than in other regions.

To find the best at-site and regional frequency distributions, we use the residual mean square error (RMSE) (Rao and Hamed, 1997) and an L-moment-based goodness-of-fit test procedure (Hosking and Wallis, 1993). The goodness-of-fit-test measure, Z^{DIST}, (Hosking and Wallis, 1993) was calculated, using a FORTRAN computer program developed by Hosking (1991), for each homogeneous region resulting from the cluster analysis. If the absolute value of Z^{DIST} is smaller than 1.64 ($\left|Z^{Dist}\right| < 1.64$), the goodness of a distribution is accepted. Table 3 shows the goodness-of fit-test measures, Z^{DIST}, for the most important 3-parameter distributions in seven groups of rainfall. For Groups 1, 3 and 4, all 3-parameter distributions are accepted. For Group 5, none of them is accepted and for groups 2, 6 and 7, some are accepted and the rest are not.

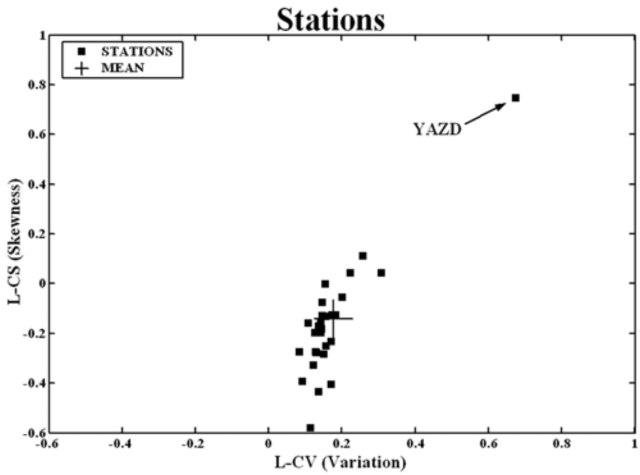

Figure 3 – Moment ratio diagrams of the selected stations.

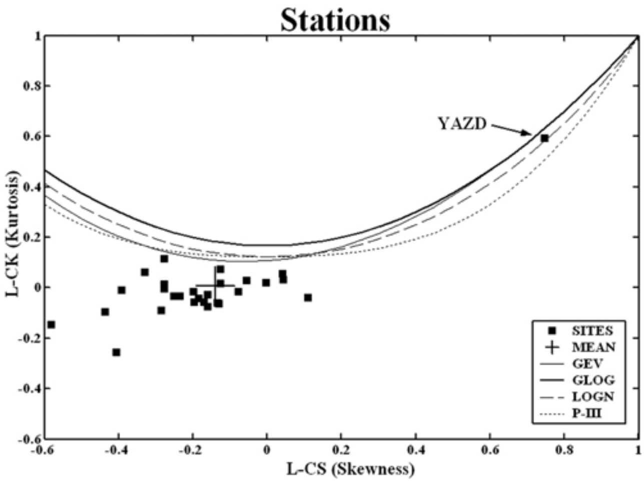

Table 3 – The goodness-of-fit-test measure (Z^{DIST}) for homogeneous rainfall groups within Iran (numbers in bold indicate distributions that are accepted).

Distributions	Iran	G1	G2	G3	G4	G5	G6	G7
Generalized Logistic	1.80	**0.34**	2.68	**0.56**	**-0.30**	-2.30	**-0.89**	**-1.09**
Generalized Extreme Value	-1.93	**-0.73**	**0.56**	**-0.60**	**-1.50**	3.89	-1.83	-1.72
3-parameter Log Normal	**-1.51**	**-0.84**	**0.87**	**-0.55**	**-1.35**	-3.47	-1.7	**-1.62**
Pearson type III	-1.81	**-1.17**	**0.76**	**-0.73**	**-1.44**	-3.48	-1.76	-1.66

Based on the goodness-of-fit-test measure, for the entire country, a 3-parameter log normal distribution seems a better fit than the other distributions. However, because of the heterogeneity of the country, this distribution is not applicable for individual regions. For each homogeneous region, a different 3-parameter distribution can be accepted. The only reliable conclusion is that for different groups, there is no single parent distribution. This indicates substantial variation of rainfall and climate, even within each homogeneous rainfall group. The result of the at-site frequency analysis also shows this rainfall spatio-temporal dissimilarity. The best at-site frequency distribution for each station is presented in Figures 4 to 11, after removing discordant stations (Yazd and Bandarabbas).

Discussion

Cluster analysis

Because of the varying spatio-temporal characteristics of rainfall across the country, a hierarchical cluster analysis was first applied to distinguish homogeneous regions. It showed that a hierarchical Ward's method could classify the rainfall spatial pattern across the country. The derived rainfall groups and geographical conditions match each other very well, with differing rainfall clusters imply varying rainfall regimes. The central arid zone of Iran (group 1) has a high coefficient of variation and low rainfall; the cold region of northwestern Iran has a high ratio of snow to rainfall (group 3). The impact of the Zagros Mountains on rainfall is evident in western Iran (group 5), with some within-region spatial variation (group 7). Other groups encompass the lowland margins of the Caspian Sea (groups 6 and 8) and the coastal stations of the Persian Gulf, except for Shiraz station (group 4). These varying rainfall groups show that the spatial pattern of rainfall of Iran is influenced by elevation, latitude and proximity to the sea (Masoodian, 1998; Domroes *et al.*, 1998). This study adds several new regions to those defined by Masoodian (1998) and Domroes (1998). The present study distinguishes two regions along the margin of the Caspian Sea, while Masoodian (1998) showed only one region. Domroes *et al.* (1998) defined two regions in the Zagros Mountains in the west of Iran, while the present study showed that this region could be divided into at least three homogeneous regions.

Frequency Analysis

The homogeneity measure showed that a 3-parameter log normal distribution can describe the overall rainfall distribution within Iran, but because of substantial variations in rainfall patterns, it is better to apply regional frequency analysis to individual homogeneous rainfall groups. However, the results showed that we cannot select a single parent distribution for each group. The regional rainfall frequency analysis indicated that different distributions can represent the different climate characteristics of rainfall groups within Iran. The Generalised Extreme Value (GEV) distribution fits the rainfall of the very high mountain stations of group 7, a region with varied mechanisms for generating rainfall, but a 2-parameter log normal (LN2) distribution fits to the high mountain stations of group 5, where there is more uniformity in rainfall generation.

A GEV distribution also fits the Persian Gulf margin and the central arid zone of Iran, which has high rainfall variation. On the other hand, the 2-parameter log normal (LN2) distribution is a better fit for rainfall in the flat humid margin of the Caspian Sea. Different at-site frequency distributions in group 2 also suggest more complex rainfall-generating mechanisms, resulting in different rainfall spatio-temporal patterns. At-site frequency analysis also indicates that frequency distributions match the rainfall

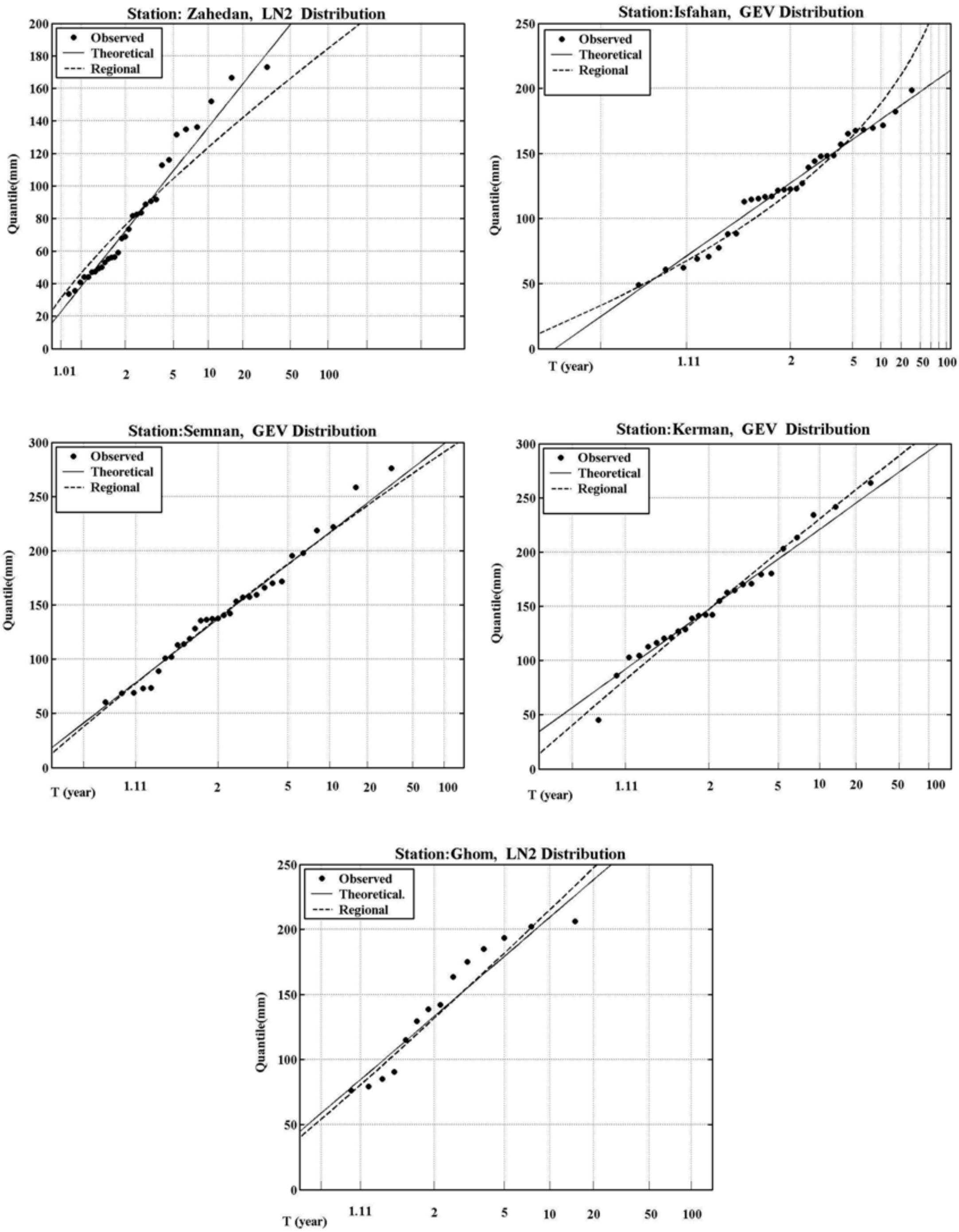

Figure 4 – Rainfall theoretical and regional probability plots for group 1.

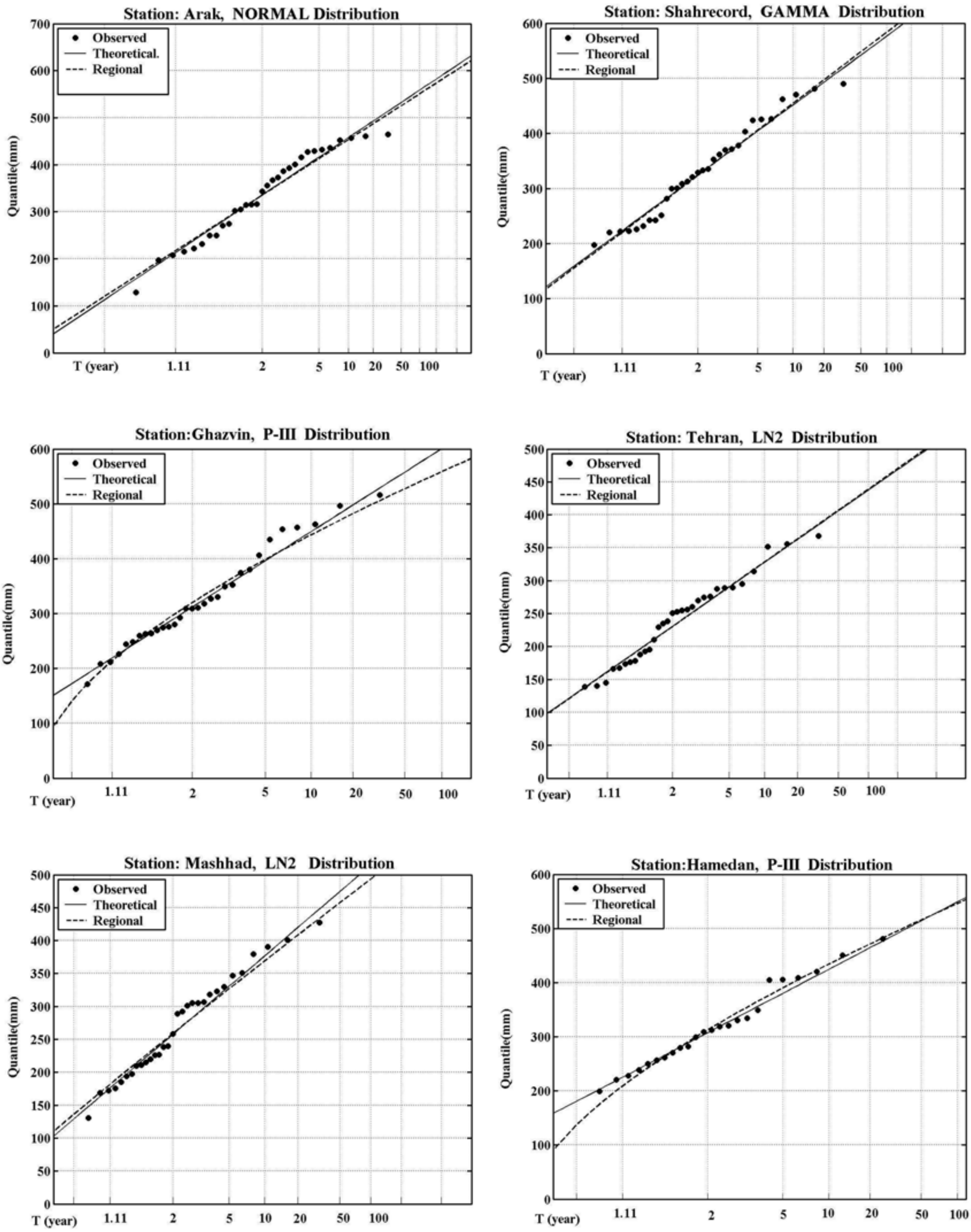

Figure 5 – Rainfall theoretical and regional probability plots for group 2.

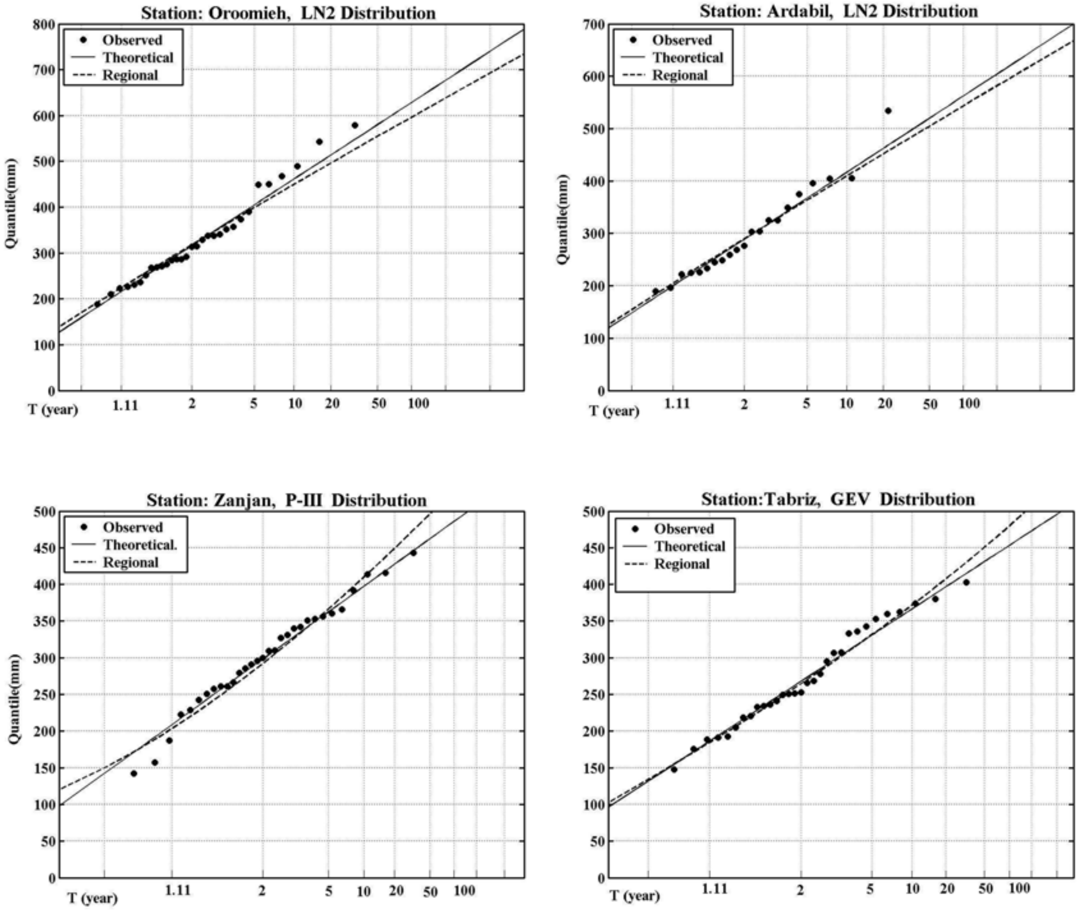

Figure 6 – Rainfall theoretical and regional probability plots for group 3.

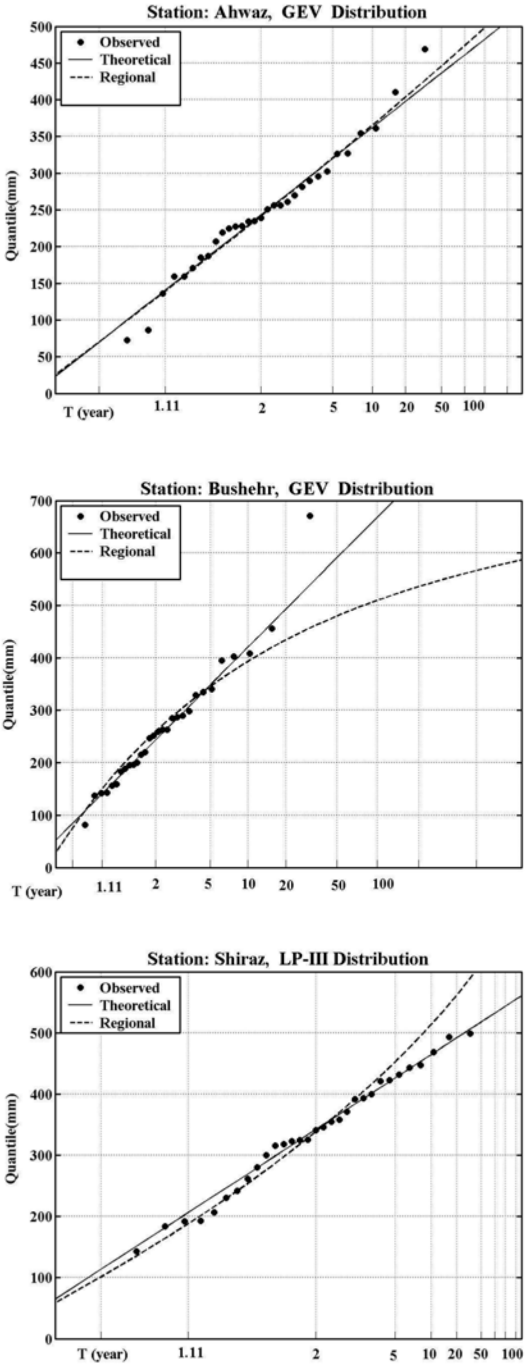

Figure 7 – Rainfall theoretical and regional probability plots for group 4.

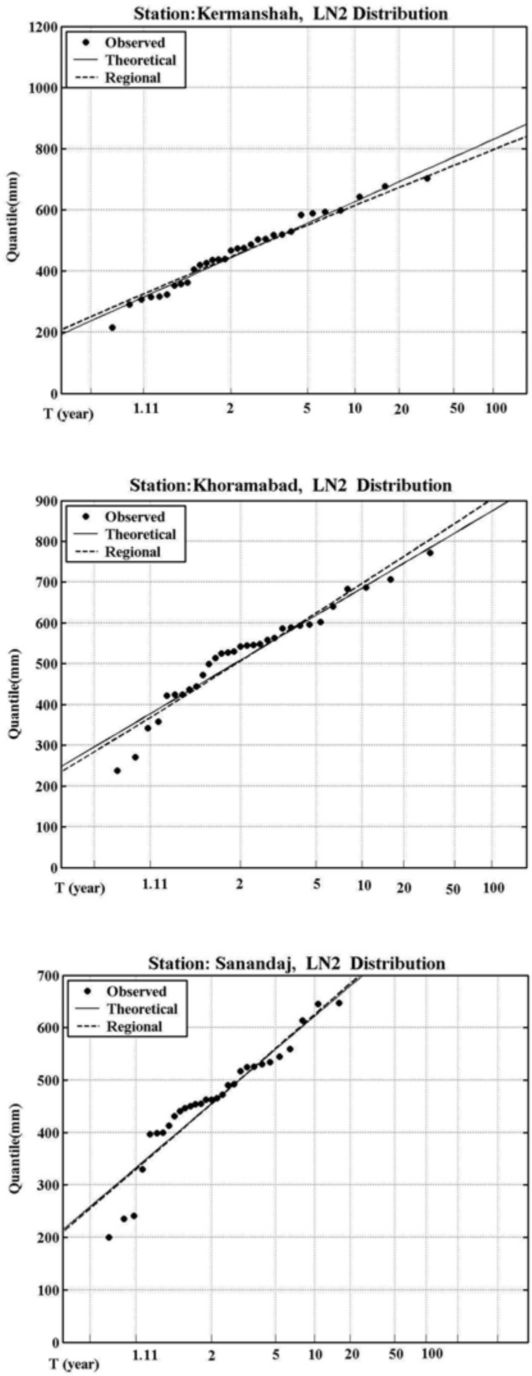

Figure 8 – Rainfall theoretical and regional probability plots for group 5.

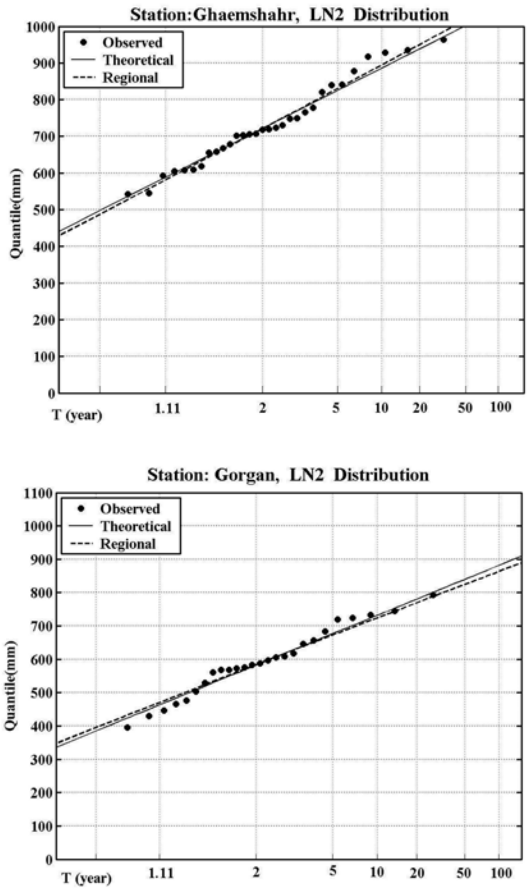

Figure 9 – Rainfall theoretical and regional probability plots for group 6.

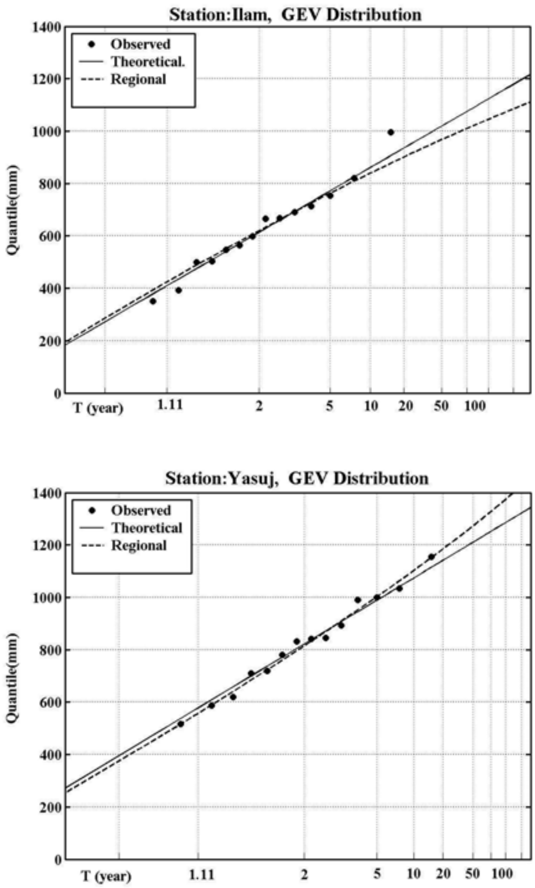

Figure 10 – Rainfall theoretical and regional probability plots for group 7

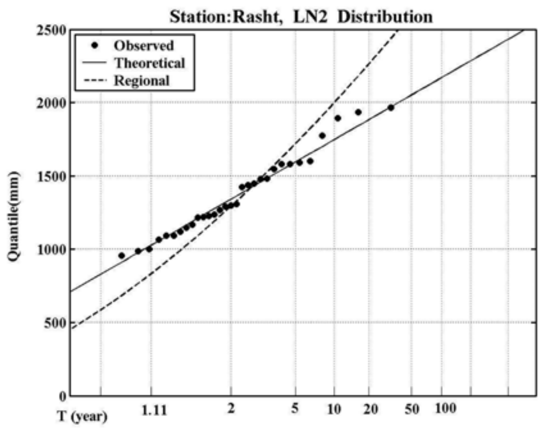

Figure 11 – Rainfall theoretical and regional probability plots for group 8.

distribution very well mainly in the range of 2-year to 10-year return periods. Outside of this range, however, the differences between the observed and predicted values increase for both at-site and regional values. The higher difference (uncertainties) for the upper and lower tail of each frequency curve could be the result of small sample size (Hosking, 1993), but these departures are frequently observed in groups with an adequate sample size (n=30), but located at the coastal margins. This may imply the influence of the sea and greater rainfall tempo-spatial variation in these regions. There is not a large difference between the observed and predicted rainfall values for interior stations, even those in group 7 (with n=13). This may confirm that there is less variation in climate conditions in the interior's homogeneous rainfall regions, except for Yazd station in the central arid zone.

Conclusion

Although homogeneity measures suggest a 3-parameter log normal (LN3) distribution for rainfall over the entire country, the considerable variation due to climatic and geographic conditions indicates this distribution is unsuitable for individual regions. It is also difficult to select a parent distribution for individual homogeneous groups due to the high degree of rainfall variation within groups. The hypothesis of the effect of geographic conditions on the type of frequency distribution can be proved in future research using a larger database. The general conclusion of this study is that three major distributions can represent rainfall frequency distributions over the country, i.e., 2-parameter log normal, Pearson type-III and GEV distributions. Thus, we can conclude that the spatial distribution of the type of the rainfall frequency distribution is not uniformly and regularly influenced by the geographic conditions. It will be a matter of ongoing investigation to develop a rainfall map of Iran for each return period to overcome the problem of the regional boundaries. Developing a dataset with more stations in each homogeneous region to improve reliability is essential for future studies, but may be difficult in some regions due to an insufficient number of stations.

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