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REGIONAL RAINFALL FREQUENCY ANALYSIS OF BHADAR BASIN USING L-MOMENT APPROACH

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ABSTRACT

Extreme rainfall events have significant consequences for human societies. Understanding the magnitudes and frequencies of rainfall is crucial for managing water resources sustainably and designing effective hydraulic structures In the present study, regional frequency analysis of maximum daily rainfalls of Bhadar basin was investigated using L-moment for 37 rainfall stations across the study area. Preliminary candidate regions are formed by the cluster analysis of site characteristics, using the average-linkage clustering and Ward's method. Several statistical tests for regional homogeneity are utilized, based on L-moment statistics. In compliance with results of the tests, the area of the Bhadar basin has been divided into four homogeneous regions. The main distinguish between higher-elevated (Region 1 and 2) consist mainly of lower mean annual precipitation total and smaller number of rainy days than lowland (Region 3 and 4) area of the Bhadar basin, whereas precipitation extremes are comparable in both regions. The study provides an estimate of the regional characteristics of rainfall that can be useful in among others flood mitigation and engineering design.

Key words: Bhadar Basin, L-Moment, Rainfall, Rainfall frequency analysis.

Introduction

Rainfall is the main source of water in India. The identification of the spatial pattern of rainfall is usually an essential need for water resources planning and management. However, the rainfall fluctuation from year to year and from place to place is usually difficult to be fully recognized. Rainfall frequency analysis plays an important role in hydrologic and economic evaluation of water resources projects. It helps to estimate the return periods and their corresponding event magnitudes, thereby creating reasonable design criteria. The basic problem in rainfall studies is an information problem which can be approached through frequency analysis. The classical approach to rainfall frequency analysis is hampered by insufficient gauging network and insufficient data, especially when the interest is in estimating events of large return periods. At-site rainfall frequency analysis is the analysis in which only rainfall records from the subject site are used. More commonly, it will be necessary to carry out a regional analysis where rainfall records from a group of similar catchments are used. Regionalization or regional analyses are thought to compensate for the lack of temporal data. Therefore, many present-day hydrologic and climatic studies are trying to find and develop methods for the regionalization of hydrologic and climatic variables. Regional classification helps scientists to simplify the hydro-climatic convolution and therefore reduce the massive body of information, observation and variables. Several methods are commonly used for the regionalization of hydro-climatic variables such as rainfall, stream flow, flood, drought, evapotranspiration and other components of the water cycle. Multivariate techniques, such as a cluster analysis (CA) and principal component analysis (PCA), are very common methods for Frequency analysis (FA) of extreme events, such as floods and droughts, has major implications in the field of water resources management. FA aims to estimate the risk associated to these events through the fitting of a probability distribution to observed data (e.g. Chow *et al.*, (1988); Lekina *et al.*, (2013). However, reliable estimations require very long station records if single station data are to be used. Regional frequency analysis (RFA) is therefore used to provide a framework for the extreme events Norbiato *et al.*, (2007). In RFA, regions are formed by grouping sites with similar hydrologic features and then hydrological information can be transferred to those target sites Hosking and Wallis (1997). However, Many authors efforts regional frequency analysis in the hydrologic literature, including Dalrymple (1960), the concept was further developed and new approaches were introduced and investigated by other researchers Vicens *et al.*, (1975); Greiss and Wood (1981); Burn (1990); Stedinger and Lu (1995); Hosking and Wallis (1997); Sveinsson *et al.*, (2001); Norbiato *et al.*, (2007); Meshgi and Khalili (2009). L-moments based statistics Hosking and Wallis (1993, 1997) are nowadays routinely used in regional analyzes. Kjeldsen *et al.*, (2002) shows the application of L-moments for regional frequency analysis of annual maximum series of flood flows in KwaZulu-Natal Province of South Africa and identified homogeneous regions and a suitable regional frequency distribution for each region. Kumar and Chatterjee (2005) employed the L-moments to define homogenous regions within 13 gauging sites of the north Brahmaputra region of India. L-moments (Hosking and Wallis, 1993, 1997) has reported many benefits and have potential of unifying current practices of regional design rainfall analysis Smithers and Schulze(2001) and proved better option to define the regional homogeneity of area. In the present study the well-known L-moment based method of the regional frequency analysis of annual maximum rainfall being utilized for the area of Bhadar basin.

Material and Methods

Study Area

The Bhadar is one of the major rivers of Kathaiwar (Saurashtra) peninsula in Gujarat. It originates near Vaddi (Aniali Village) about 26 km north – west of Jasdan in Rajkot district at an elevation of 261 m above mean sea level. It flows towards South up to Jasdan and turns towards south - west upto Jetpur and finally changes its direction towards west till its confluence with Arabian sea at Navibandar (Porbandar). The total length of this river is 198 km. It has a drainage area of 7094 sqkm out of which 706 sqkm is in hilly and the rest in plain regions of Saurashtra. The basin lies between geographical co-ordinates of 21°25’ and 22°10’ north latitudes and 69°45’

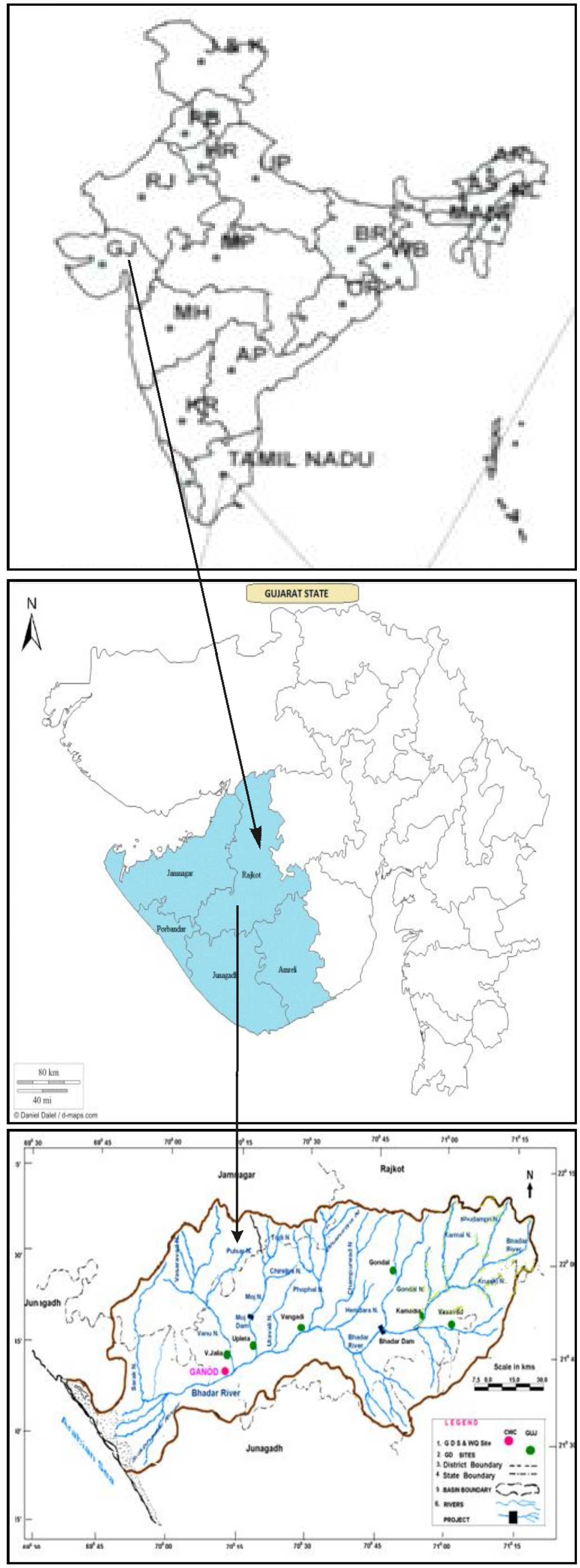

Fig. 1: Location map of Bhadar basin.

Table 1: List of the 37 rain gauge stations and associated characteristics in the Bhadar basin.

Site No.	Site Name	Latitude	Longitude	Record length (yr.)	Mean Precipitation Days	Mean Annual Precipitation	Elevation
1	Alansagar	22.0747	71.1989	49	16.58	359.41	218
2	Amarnagar	21.7500	70.7936	46	17.59	548.79	113
3	Amipur	21.4089	69.9442	28	33.99	569.79	15
4	Bhadar-I	21.8119	70.7600	48	33.82	574.80	104
5	Boriya	21.9203	70.5000	35	20.96	458.21	110
6	Chhaparvadi-I	22.0272	70.6700	45	20.99	439.78	129
7	Chhaparvadi-II	21.8747	70.6042	46	23.70	588.58	95
8	Dadar	22.0181	70.3617	47	16.98	389.44	125
9	Dhoraji	21.7383	70.4489	59	29.86	599.69	65
10	Dhrafa	21.9633	70.1067	17	16.52	578.33	118
11	Gondal	21.9617	70.8008	60	31.26	549.39	134
12	Gondali	22.0228	70.8356	53	24.29	556.21	149
13	Gulabsagar	21.8458	69.7919	32	14.99	491.07	77
14	Ishwariya	21.9703	71.0192	27	23.58	503.34	151
15	Jam-Jodhpur	21.8997	70.0364	59	34.39	623.17	95
16	Jam-Kandorana	21.8931	70.4928	51	32.59	569.90	102
17	Jasdan	22.0700	71.2200	45	30.19	508.33	209
18	Jetpur	21.7594	70.6261	60	33.59	639.29	92
19	Kamadhiya	21.8528	70.9167	40	32.67	565.93	118
20	Kotda-Sangani	22.0450	70.8122	51	28.39	514.38	156
21	Lodhika	22.1361	70.6333	56	29.11	560.18	160
22	Moj	21.8361	70.2767	55	24.86	577.19	71
23	Nagvadar	21.7500	70.2039	33	29.48	519.12	46
24	Phophal	21.8497	70.5119	47	31.97	569.05	77
25	Rajavadala	22.0953	71.1722	49	16.71	348.70	217
26	Rana-Kandorana	21.6397	69.8867	23	36.99	638.78	25
27	Revaniya	22.1997	71.3250	48	14.15	318.59	202
28	Samana	22.1022	70.1456	34	15.49	540.40	167
29	Sankroli	21.6514	70.7661	48	29.58	529.93	132
30	Seth-Vadala	22.0272	70.1358	34	15.15	461.51	136
31	Upleta	21.7303	70.2783	52	33.58	626.17	40
32	Vachhapari	22.0686	70.8639	46	25.83	558.12	171
33	Vasavad	21.8269	71.0236	27	26.98	466.94	140
34	Vegdi	21.7967	70.4867	22	39.76	639.91	55
35	Venu-II	21.8294	70.1553	44	23.79	518.81	60
36	Veri	22.0000	70.8047	53	23.08	587.91	142
37	Vinchhiya	22.2111	71.3808	36	15.21	376.93	175

and 71^{o}20' east longitudes. It drains about 1/7th of the area of Saurashtra. In the present study, daily rainfall data (1961-2020) of 37 gauge stations, compiled by State Water Data Center, Gandhinagar have been analyzed. The study was limited, by necessity, to daily data In addition, information on longitude, latitude, and mean elevation above sea level was also obtained for each site. Fig. 1 shows the location of the Bhadar basin and the 37 rainfall gauge stations with basic information presented in Table 1.

Preliminary Screening of Data

Stationarity and independence are important underlying assumptions inherent to frequency analysis. Without stationary and serial correlation tests, the analysis may lead to incorrect results and conclusions. Another requirement is that data at different stations in a homogeneous region should be spatially independent. High spatial cross-correlation between stations gives a lower degree of additional regional information to the site being studied than uncorrelated sites Ngongondo *et al.*, (2011). Stationarity is examined using the nonparametric Mann-Kendall (MK) trend test Mann (1945); Kendall (1975) independence is tested using lag-1 to lag-5 autocorrelation and Moren's I Moren (1950) is used to test for spatial independence.

Regional Frequency Analysis

The methodology that was used here for regional frequency analysis of maximum daily rainfalls in the Bhadar province is an index variable approach based on L-moments as outlined by Hosking and Wallis (1997). L-moments was applied in three steps of the regional frequency analysis to identify regional homogeneity Hosking and Wallis (1997); these were i) identification of candidate homogeneous region using cluster analysis ii) screening of the data using the discordancy measure D_i iii) homogeneity testing using the heterogeneity measure H.

Identification of candidate homogeneous region using cluster analysis

A hierarchical cluster analysis is carried out using Ward's method applying Squared Euclidean Distance as the distance or similarity measure. This helps to determine the number of clusters to work with. The statistical package for social sciences (SPSS) was used in this study to select number of clusters. The formation of candidate regions was based, in accordance with common practice Hosking and Wallis (1997), on the cluster analysis of 'site characteristics': longitude, latitude, elevation, maximum annual precipitation, mean annual precipitation and mean annual number of rainy days.

Screening of the data using the discordancy measure D_i

Hosking and Wallis (1993) derived two statistics to test the homogeneity of the region. The first statistic is discordancy measure (D_i), is a measure of dissimilarity. D_i is a statistic based on the difference between L-moment ratios of a site and the average L-moment ratios of a group of similar sites. This statistic can also be used to identify erroneous data. The discordancy measure for site i define as follow;

$$D_i = \frac{1}{4} N_k (u_i - \bar{u})^T S^{-1} (u_i - \bar{u}) \tag{1}$$

Where, Nk is number of sites in region, ui is a vector containing three L-moment ratios (*i.e.*, L-Cv, L-skewness and L-kurtosis) for site i, $\bar{u}$ un weighted group average of the L-moment ratios and S is the sample covariance matrix of L-moments of all sites. Generally, any site with D_i>3 is considered discordant Hosking and Wallis (1993); Adamowski (2000).

Homogeneity testing using the heterogeneity measure H

The second criterion, called H-statistic, is a measure of heterogeneity. This statistic compares the between-site variability (dispersion) of L-moments with what would be expected for a homogeneous region. The test compares the variability of L-statistics of the actual region to those of the simulated series. There are three heterogeneity measurers, namely H_1, H_2 and H_3, which are calculated using the following equation:

$$H_i = \frac{\left(V_i - \mu_{V_i}\right)}{\sigma_{V_i}} \tag{2}$$

Where μ_v and σ_v are the mean and standard deviation of N_{sim} values of V (N_{sim} is the number of simulation data). V_i is calculated from the regional data based on V statistic. A region is declared "acceptably homogeneous" if *H*<1 "Possibly homogenous/heterogeneous" if 1<*H*<2 and "Definitely heterogeneous" if H>2 Hosking and Wallis (1997).

Results and Discussion

Test for Stationarity, Serial Independence and Spatial Independence

The preliminary process of data (*i.e.*, examining the stationarity, serial independence and spatial independence)

Fig. 2: Autocorrelation function analysis plots of maximum daily rainfall series for 37 rain gauge stations.

Table 2. Results of the trend analysis of maximum daily rainfall series using the Mann-Kendall test.

Site No.	Site Name	Mann-Kendall (Z)	Sig.
1	Alansagar	1.21	NS
2	Amarnagar	0.59	NS
3	Amipur	0.07	NS
4	Bhadar-I	1.27	NS
5	Boriya	0.40	NS
6	Chhaparvadi-I	0.17	NS
7	Chhaparvadi-II	0.07	NS
8	Dadar	1.63	NS
9	Dhoraji	1.09	NS
10	Dhrafa	0.00	NS
11	Gondal	1.12	NS
12	**Gondali**	**1.95**	*
13	Gulabsagar	0.08	NS
14	Ishwariya	1.25	NS
15	Jam-Jodhpur	0.23	NS
16	Jam-Kandorana	0.12	NS
17	Jasdan	0.68	NS
18	Jetpur	1.25	NS
19	Kamadhiya	0.85	NS
20	Kotda-Sangani	1.40	NS
21	Lodhika	0.00	NS
22	Moj	0.80	NS
23	Nagvadar	0.69	NS
24	Phophal	0.23	NS
25	Rajavadala	1.20	NS
26	**Rana-Kandorana**	**2.38**	*
27	Revaniya	0.71	NS
28	Samana	0.30	NS
29	**Sankroli**	**3.45**	*
30	Seth-Vadala	0.68	NS
31	Upleta	1.10	NS
32	Vachhapari	1.61	NS
33	Vasavad	1.10	NS
34	Vegdi	0.00	NS
35	Venu-II	0.47	NS
36	Veri	1.23	NS
37	Vinchhiya	1.17	NS

was carried out using the Mann-Kendall test, autocorrelation coefficients and Moran's I test to verify that the maximum daily rainfall data are appropriate for regional frequency analysis.

The results of the Mann-Kendall trend test are presented in Table 2, from which it can be seen that out of 37 rainfall stations, only three stations demonstrate a statistically significant trend and remaining 34 stations show no significant trends at 5% significance level. At most observations of maximum daily rainfall in the study region do not have significant trends, it is reasonable to infer that trends are not significant at the regional level and data can be treated as stationery series. The value of autocorrelation coefficients for lags 1 to 5 are plotted in the correlograms presented in Fig. 2, where the solid

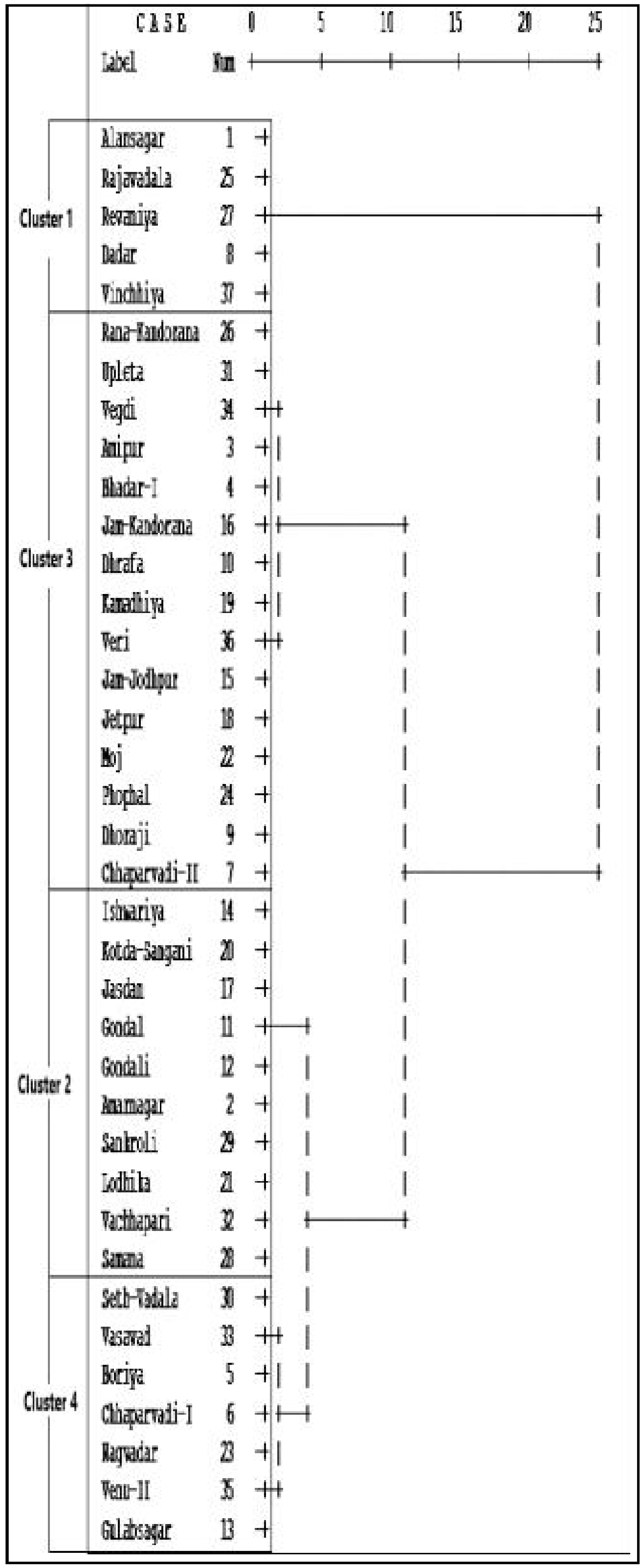

Fig. 3: Dendogram.

Table 3: Value of discordancy measure (D_i) for all region with sites.

No.	Site Name	D_i
	Region 1	
1	Alansagar	1.319
8	Dadar	1.227
25	Rajavadala	0.973
27	Revaniya	0.358
37	Vinchhiya	1.124
	Region 2	
2	Amarnagar	1.252
11	Gondal	1.363
12	Gondali	0.312
14	Ishwariya	1.324
17	Jasdan	0.877
20	Kotda-Sangani	0.329
21	Lodhika	0.899
28	Samana	2.229
29	Sankroli	0.797
32	Vachhapari	1.194
	Region 3	
3	Amipur	0.102
4	Bhadar-I	0.024
7	Chhaparvadi-II	2.163
9	**Dhoraji**	**4.380***
10	**Dhrafa**	**4.196***
15	Jam-Jodhpur	0.069
16	Jam-Kandorana	0.387
18	Jetpur	0.136
19	Kamadhiya	0.518
22	Moj	0.196
24	Phophal	0.230
26	Rana-Kandorana	0.210
31	Upleta	0.142
34	Vegdi	0.979
36	Veri	1.168
	Region 4	
5	Boriya	0.714
6	Chhaparvadi-I	0.494
13	Gulabsagar	1.531
23	Nagvadar	0.298
30	Seth-Vadala	0.998
33	**Vasavad**	**1.923***
35	Venu-II	1.220

horizontal lines are intended to give critical values for testing whether or not the autocorrelation coefficients are significantly different from zero. It can be seen that for almost all stations autocorrelation coefficients within the critical bounds, thus we might well consider the maximum daily rainfall series as time-independent.

The results of Moren's I calculations suggested that cross-correlation among the stations was not statistically significant at the 5% level and the data series can be considered spatially independent.

Cluster Analysis

As described in the methodology section, a hierarchical cluster analysis with Ward's method was first applied to identify initial homogeneous regions. The result of Ward's clustering with four clusters is depicted in the dendrogram drawn in Fig. 3. The rainfall clusters were reviewed to assess whether they are spatially continuous and physically reasonable. The spatial distribution of the rainfall groups is illustrated in Fig. 4. The first region located in the eastern arm of the Bhadar basin with an average altitude of 187 masl. Mean annual rainfall (MAR) was around 359 mm with average annual maximum rainfall (AMR) 73 mm. The second region was comprised of ten stations located along the ridge and northern central part of Bhadar basin with surrounding medium altitude areas with average altitude of 154 masl. The region had a MAR of around 535 mm with average AMR 105 mm. The third region had 15 stations mostly located in the central lowlands with average altitude of 80 masl. MAR was 596 mm and average AMR was 118 mm. The third regions raingauge stations having high rainfall areas as compared to other regions and located around the Bhadarbasin.

A combination of convective processes over land and adjacent water are major influences of intense rainfall in the region. The fourth homogenous region is formed by seven stations situated in the upland crest of Bhadar basin in western parts but in the leeward southern face. This region has an average altitude of 100 masl and mean

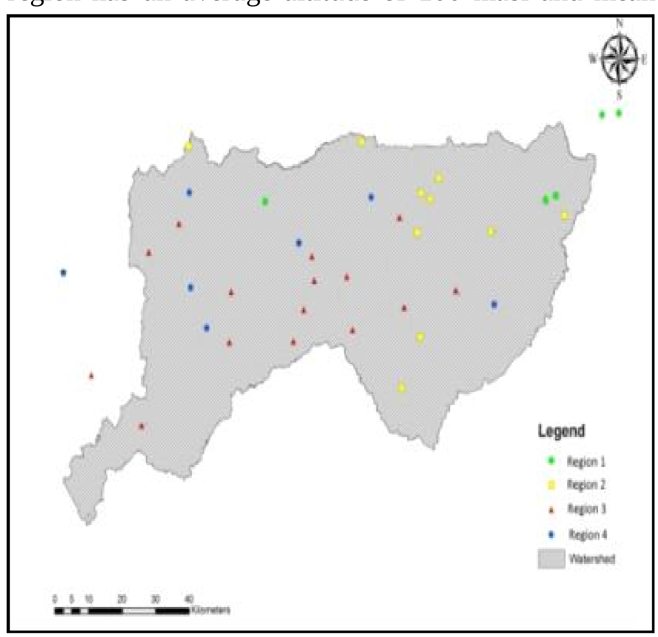

Fig. 4: The spatial distribution of the rainfall group.

Table 4: Heterogeneity measures including discordant site.

Region	No. of site	H_1	Judg-ment	H_2	Judg-ment	H_3	Judg-ment
Region-1	**5**	0.851	HR	-0.245	HR	-0.431	HR
Region-2	**10**	-0.813	HR	-0.749	HR	-0.803	HR
Region-3	**15**	0.879	HR	1.468	PHR	1.456	PHR
Region-4	**7**	-0.918	HR	-0.473	HR	-0.223	HR
PHR: Possibly homogeneous region, HR: Homogeneous region							

annual precipitation of 479 mm and AMR of 107 mm.

Discordancy measures

The discordancy measures together with the sample L-moment ratios for the four regions of Bhadar basin are given in Fig. 5. The result of the discordancy test for these four groups indicates that there are no discordant station within the groups except for the Region 3 and Region 4. The critical value 1.333 and 2.491 are not exceeding for the sites of region 1 and region 2 respectively, so both the region is homogenous. The critical value 3 is exceeded at two sites of region 3, *i.e.* Dhoraji and Dhrafa, which have discordancy measures of 4.38 and 4.19, respectively. It can be seen from Fig. 5 that Dhoraji has the lowest L-skewness but high L-kurtosis and Dhrafa has very high L-CV but low L-skewness and L-kurtosis. Therefore, these two sites are excluded from the regional frequency analysis. One possible reason for the exceptional results of site Dhrafa has the shortest time series 17 years, which makes the unreliable high-moments. It is observed for the region - 4 that only Vasavad site has higher D_i value *i.e.* 1.923 than critical value 1.917. It can be seen that despite the data being positive skewed, neither outliers nor unusual data are detected. Therefore, the higher D_i may be due to its higher L-skewness and L-kurtosis and shorter length of record. The positions of sample L-moment ratios in the region are scattered as expected (Fig. 5), and the results of the discordancy measure for other sites are shown to be satisfactory.

Table 5: Heterogeneity measures excluding discordant site.

Region	No. of site	H_1	Judg-ment	H_2	Judg-ment	H_3	Judg-ment
Region-1	**5**	0.851	HR	-0.245	HR	-0.431	HR
Region-2	**10**	-0.813	HR	-0.749	HR	-0.803	HR
Region-3	**15**	-0.440	HR	-0.164	PHR	-0.017	HR
Region-4	**7**	-0.910	HR	-0.483	HR	-0.184	HR
PHR: Possibly homogeneous region, HR: Homogeneous region							

Homogeneity testing

The positions Hosking and Wallis's heterogeneity statistics have been calculated for the four identified homogeneous regions with including and excluding discordant site in Table 4 and Table 5 respectively. According to the critical values of H_1, H_2 , and H_3 , the region – 3 appeared to be possibly homogenous/ heterogeneous with discordant site but ignoring discordant site has reduced the values of heterogeneity statistics and no occurrences of values of the test statistic of the Hosking-Wallis tests larger than or equal to 2 ('definite heterogeneity') throughout the perturbed samples. So, all four regions of Bhadar basin can be considered as homogeneous. Kjeldsen *et al.*, (2002) applied the L-moments for regional frequency analysis of annual maximum series of flood flows in KwaZulu-Natal province of South Africa and identified homogeneous regions, while Kumar and Chatterjee (2005) identified homogenous regions within 13 gauging sites of the north

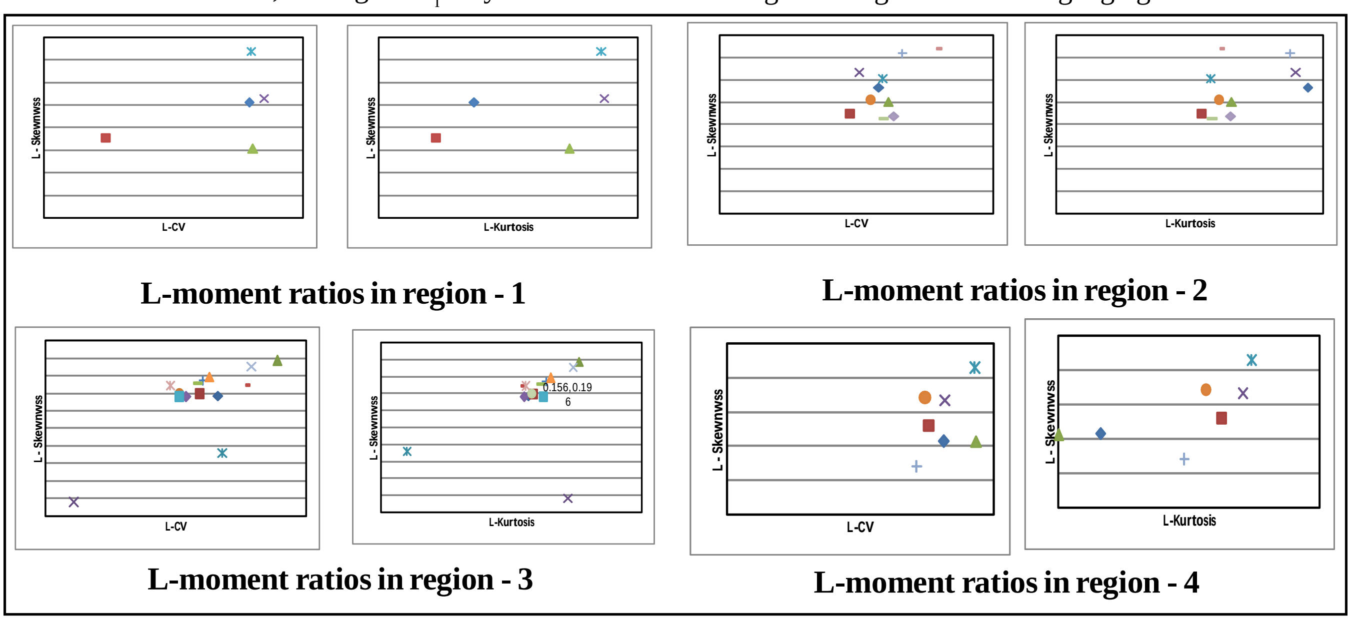

Fig. 5: L-moment ratios in all region.

Brahmaputra region of India using L-moment approach.

Conclusion

Overall, it was found that cluster analysis together with the L-moments based regional frequency analysis technique can be applied successfully in deriving rainfall based regional homogeneity of Bhadar basin. The regional approach using L-moments may be useful in improving estimates of future changes in precipitation derived from climate models. Nevertheless, it should be noted that, since the regions configured are not only homogeneous as to the statistical characteristics of rainfall, but also reflect climatological differences in precipitation regimes and their future application for the purpose of planning for weather-related emergencies and design of hydraulic engineering structures.

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