

# Characterizing Rainfall of Hot Arid Region by Using Time Series Modeling and Sustainability Approaches: A Case Study from Gujarat, India

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## Abstract

This study aimed at characterization of rainfall dynamics in a hot arid region of Gujarat, India by employing time series modelling techniques and sustainability approach. Five characteristics, i.e. normality, stationarity, homogeneity, presence/absence of trend, and persistence of 34-year (1980-2013) period annual rainfall time series of ten stations were identified/detected by applying multiple parametric and nonparametric statistical tests. Furthermore, the study involves novelty of proposing sustainability concept for evaluating rainfall time series, and demonstrated the concept, for the first time, by identifying the most sustainable rainfall series following reliability ( $R_y$ ), resilience ( $R_e$ ) and vulnerability ( $V_y$ ) approach. Box-whisker plots, normal probability plots and histograms indicated that the annual rainfall of Mandvi and Dayapar stations is relatively more positively-skewed and non-normal compared to that of other stations, which is due to the presence of severe outlier and extreme. Results of Shapiro-Wilk test and Lilliefors test revealed that annual rainfall series of all stations significantly deviated from normal distribution. Two parametric t-tests and the nonparametric Mann-Whitney test indicated significant non-stationarity in annual rainfall of Rapar station, where the rainfall was also found to be non-homogeneous based on the results of four parametric homogeneity tests. Four trend tests indicated significantly increasing rainfall trends at Rapar and Gandhidham stations. The autocorrelation analysis suggested the presence of persistence of statistically-significant nature in rainfall series of Bhachau (3-year time lag), Mundra (1- and 9-year time lag), Nakhatrana (9-year time lag) and Rapar (3- and 4-year time lag). Results of sustainability approach indicated that annual rainfall of Mundra and Naliya stations ( $R_y=0.50$  and  $0.44$ ;  $R_e=0.47$  and  $0.47$ ;  $V_y=0.49$  and  $0.46$ , respectively) are the most sustainable and dependable compared to that of other stations. The highest values of sustainability index at Mundra (0.120) and Naliya (0.112) stations confirmed the earlier findings of  $R_y$ - $R_e$ - $V_y$  approach. In general, annual rainfall of the study area is less reliable, less resilient and moderately vulnerable, which emphasizes the need of developing suitable strategies for managing water resources of the area on sustainable basis. Finally, it is recommended that multiple statistical tests (at least two) should be used in time series modelling for making reliable decisions. Moreover, methodology and findings of the sustainability concept in rainfall time series can easily be adopted in other arid regions of the world.

**Key words:** Normality; Stationarity; Homogeneity; Trend; Persistence; Reliability; Resilience; Vulnerability; Sustainability index;

## 1. INTRODUCTION

Rainfall, a vital component of water cycle, plays a significant role in water resources management by meeting domestic and agricultural water demands, conserving soil and water resources, improving surface water and groundwater water quality, maintaining groundwater levels, etc. Information on spatial and temporal patterns of rainfall time series based on historical datasets is necessary for various climatological and hydrological applications such as detection of climate variability/change (Delitala et al., 2000), realistic assessment of water resources, estimation of probable maximum precipitation, understanding eco-hydrological processes (Oguntunde et al., 2006; Cannarozzo et al., 2006) and hydrological modelling of a basin (Beven, 2001).

Importance of spatio-temporal analysis of rainfall is further increased for arid lands, which experience an overall water deficit scenarios due to less frequency and relatively low rainfall occurrences, and extends over 61 million km<sup>2</sup> worldwide (46% of the global area) (FAO Terrastat Database, 2003). In India, arid lands are spread over 50.8 million ha, which is 15.8% of the country's geographical area (MoEF, 2001; NBSS&LUP, 2001). The country's arid zone can be further sub-divided into (i) hot arid and (ii) cold arid zones. The major portion of the Indian hot arid zone, occupying about 32 million ha, falls in western Rajasthan (62% of country's hot arid zone) and Gujarat (19.6% of country's total arid land) (Kar et al., 2009). Kachchh (study area), the second largest district of the country, is situated in Gujarat State and experiences hot and arid climate over the entire land (Harsh and Tewari, 2007; Dayal et al., 2009). The study area comes under sensitive seismic zones of the country with very high vulnerability of occurring earthquakes; one of the major earthquakes occurred in January 2001. Rainfall in the study area is highly erratic and unpredictable in nature. Scarcity of surface water resources is a common phenomenon in the study area and groundwater resources are mostly unusable due to deeper availability and considerable coastal salinity. Therefore, it is necessary to understand rainfall dynamics over spatial and temporal scales in the study area, which is the first step towards management of sustainable water resources under changing climate.

Time series modelling offers a comprehensive technique to investigate temporal patterns of a rainfall time series through detection of all important characteristics of a time series, i.e. normality, stationarity, homogeneity, presence/absence of trend and persistence (Shahin et al., 1993; Adeloye and Montaseri, 2002; Machiwal and Jha, 2006; Machiwal and Jha, 2008; Machiwal and Jha, 2012). Homogeneity implies that the entire data in the time series belong to one population, and therefore, have a time-invariant mean. In general, non-homogeneity in the time series arises due to changes in the method of data collection and/or the environment in which it is done (Fernando and Jayawardena, 1994). Stationarity implies that the statistical

parameters of the time series computed from different samples do not change, except due to sampling variations. Trend exists in a time series dataset if there is a significant correlation between the observations and time. Trends in hydrological series are normally introduced through natural or anthropogenic activities (Shahin et al., 1993). Persistence is the tendency for the magnitude of an event to be dependent on the magnitude of the previous event(s).

Analysis for detecting time series characteristics is inevitable for water resources studies involving use of rainfall time series data (Adeloye and Montaseri, 2002). But it is seen that mostly time series analysis is overlooked in past studies dealing with rainfall data series assuming that ignorance of such time series characteristics will not affect the results (Rao et al., 2003). Furthermore, it is observed from literature survey that except dealing with linear trend analysis, rest of the time series characteristics of equal importance, e.g. normality, homogeneity, stationarity and persistence are ignored. An extensive literature survey of past studies on rainfall time series analysis revealed that studies examining time series characteristics of rainfall in humid and/or semi-arid regions are numerous (Mirza et al., 1998; Pugacheva et al., 2003; Astel et al., 2004; Machiwal and Jha, 2008; Kumar et al., 2010; Deka et al., 2014; Goyal, 2014; Talaei, 2014); but such studies for arid regions are rare (e.g. Modarres and da Silva, 2007).

The concept of sustainable development was introduced, for the first time, about 35 years ago by the World Conservation Strategy (IUCN, 1980). The sustainability index (SI) was initially proposed to evaluate the performance of alternative policies from the perspective of water users and the environment. In other words, the SI can be defined as a measure of a system's adaptive capacity to reduce its vulnerability. Thus, if the system is made more sustainable by implementing a policy, the SI will indicate that the system has larger adaptive capacity. The concept of SI was first defined by Loucks (1997) using reliability (R), resilience (R) and vulnerability (V) as the performance criteria with an aim to evaluate and compare water management policies. Thereafter, the index has been utilized by researchers for the scientific use (McMahon et al., 2006; Ray et al., 2010; Sandoval-Solis et al., 2011). In general, the R-R-V based sustainability concept is used to evaluate performance of the water resources systems (Loucks, 1997; Kay, 2000; Ajami et al., 2008; Sandoval-Solis et al., 2011). It is revealed from literature that the sustainability concept has never been applied to evaluate performance of hydrologic time series. Thus, in this study, sustainability concept is proposed, for the first time, to evaluate performance of the rainfall time series based on R-R-V approach.

This study aims at characterization of rainfall in an arid region by using time series modelling techniques by identifying/detecting salient time series characteristics. Unlike the usual approach, this study applies adequate number of parametric and non-parametric statistical tests. Moreover, this study proposes the novel concept of sustainability using the R-R-V approach. The proposed approach is first time used to evaluate sustainability of the rainfall

time series for ten rainfall stations of the study area in order to identify the most sustainable rainfall time series.

## **2. MATERIALS AND METHODS**

### **2.1 Study Area Description**

Kachchh district (study area) is situated in a crescent-shaped peninsula from 22°44'08" to 24°41'30" north latitudes and 68°07'23" to 71°46'45" east longitude in Gujarat state of western India (Fig. 1). It is the largest district in Gujarat encompassing an area of 45,612 km<sup>2</sup> (23% area of Gujarat) and second largest district of the country after Leh. The study area somewhat looks like an island bounded by the Gulf of Kachchh and the Arabian Sea in south and west and by the Ranns (salty marshlands) in the east and north directions. Entire Kachchh district is sub-divided into ten blocks for administrative purposes: Bhuj and Nakhatrana in the north, Lakhpat and Abdasa in the west, Mandvi, Mundra, Anjar and Gandhidham in the south, and Bachau and Rapar in the east. Gandhidham is relatively new block established in the year 1997.

Rainfall in the study area is highly erratic and low with 100-year mean annual rainfall of 341 mm (Source: [http://indiawaterportal.org/met\\_data/](http://indiawaterportal.org/met_data/)). The study area experiences the highest air temperature in May, whereas the air temperature remains the lowest in January month. The mean monthly maximum air temperature ranges from 22.1 to 31.9 °C whereas, the mean monthly minimum air temperature varies from 8.8 to 22.7 °C based on 100-year datasets (Source: [http://indiawaterportal.org/met\\_data/](http://indiawaterportal.org/met_data/)). In general, relative humidity in the coastal part is high throughout the year, exceeding 60% on an average. Relative humidity is above 80% in the coastal region and more than 65% inland during the southwest monsoon. During rest of the year, the air is generally dry and the relative humidity in the afternoon falls below 25%. The normal potential evapotranspiration varies from 1750 mm/year in the coastal area of Naliya, Mandvi and Mundra to 1900 mm/year towards Bhuj and Anjar. Towards the north and northeast, the values decrease up to 1800 mm/year and less. In general, evapotranspiration is 4-5 times higher than the precipitation, leaving a large water deficit in the area (Singh and Kar, 1996).

### **2.2 Data Description**

In this study, rainfall data of ten rainfall gauging stations namely Naliya, Anjar, Bhachau, Bhuj, Gandhidham, Dayapar, Mandvi, Mundra, Nakhatrana and Rapar were utilized; location of the rainfall gauging stations is shown in Fig. 1. Of the ten rainfall stations, eight are situated at the block headquarter; rainfall station for Abdasa and Lakhpat blocks are situated at Naliya and Dayapar, respectively. The rainfall data were collected for a period of 34 years (1980-2013) from State Emergency Operation Centre and State Flood Control Room, Revenue Department, Gandhinagar, Gujarat, India. Since the Gandhidham was made as separate block in the year 1997, rainfall station in the block was established in the year 1998

for continuous monitoring of the rainfall. The collected data were used to prepare consistent and regular annual rainfall time series for the ten rainfall stations.

### **2.3 Parametric and Non-Parametric Approaches for Time Series Analysis**

In annual rainfall time series of the ten stations, time series characteristics, i.e. normality, homogeneity, stationarity, presence/absence of trend and persistence were identified/detected by applying multiple statistical tests, both parametric and non-parametric in nature, for each characteristic. A total of six tests were applied for normality (box-whisker plots, histograms, normal probability plots, Shapiro-Wilk test, Lilliefors test, Kolmogorov-Smirnov test), four tests for homogeneity (Tukey test, Link-Wallace test, Bartlett test and Hartley test), three tests for stationarity (Student's t-test, Simple t-test and Mann-Whitney test), three tests for detecting presence of trend (Kendall Rank Correlation test, Spearman Rank Order Correlation test and Mann-Kendall test) and autocorrelation analysis method for testing persistence in rainfall time series.

Both graphical as well as statistical methods were employed in this study to examine normality of the rainfall time series. Such a combined approach is suggested as the best way to decide whether time series data are normal or not (Machiwal and Jha, 2012). The homogeneity tests applied in this study are of parametric nature, which requires that the population should be normally-distributed with equal variances. Of the four homogeneity tests, Link-Wallace test has limitation that sample size of all populations should be equal. Of the three stationarity tests, two (Student's t-test and simple t-test) are parametric requiring normality be present in the rainfall data, while the Mann-Whitney test is nonparametric without having any assumption. The most common approach for detecting trends is linear/regression model between data and time but this parametric test does not distinguish between trend and persistence (Hameed et al., 1997). This test can also be misleading under presence of seasonality and data correlation, and absence of normality (Gilbert, 1987). The problems associated with parametric regression test is overcome by nonparametric Spearman Rank Order Correlation (SROC) test (McGhee, 1985) recommended by the World Meteorological Organization (WMO, 1988). Two excellent, more powerful and widely-used nonparametric trend detection tests are Kendall Rank Correlation (KRC) test and Mann-Kendall (M-K) test (Hirsch et al., 1982; Jayawardena and Lai, 1989; Gan, 1992; Zipper et al., 1998; Kumar, 2003; Machiwal and Jha, 2008; Machiwal and Jha, 2014; Machiwal and Jha, 2015). The M-K test also indicates increasing or declining nature of the trend. Moreover, time domain (autocorrelation method) approach for testing persistence in rainfall time series is preferred over frequency domain or spectral method (Quimpo, 1968) due to the fact that the spectral density is a Fourier transform of the autocorrelation function (Machiwal and Jha, 2012). Details about all the time series modelling tests can be found in standard textbooks on hydrologic time series analysis (e.g. Shahin et al., 1993; Machiwal and Jha, 2012), and therefore, test-procedures are omitted here to avoid excessive length of the paper.

## 2.4 Sustainability Index for Rainfall Time Series

This study utilized novel concept of sustainability index for a rainfall time series, which can be expressed as a function of reliability, resilience and vulnerability (R-R-V) criteria. In this study, sustainability of the rainfall time series of ten rainfall gauging stations is compared through R-R-V approach in order to identify the most sustainable rainfall time series over a period of 34-years with respect to long-term mean threshold value of the rainfall in the study area. The estimators of reliability, resilience, vulnerability and sustainability index are described ahead.

### 2.4.1 Reliability

Water demand reliability of the water resources systems is the probability that the available water supply meets the water demand during the period of simulation (Klemes et al., 1981; Hashimoto et al., 1982). The ‘reliability’ of a time series is defined as the number of data in a satisfactory (successful) state divided by the total number of data in the time series. Assuming satisfactory values in the rainfall time series  $x_n$  containing  $n$  values are those equal to or greater than some threshold  $x^T$ , the reliability of the system can be expressed as (Machiwal and Jha, 2012):

$$R_y = f_{SE} / n \quad (1)$$

Where,  $R_y$  = reliability;  $f_{SE}$  = number of successful events or satisfactory values in rainfall time series ( $x_n$ ), when  $x_t \geq x^T$  ( $t=1, 2, \dots, n$ ); and  $n$  = sample size of time series.

### 2.4.2 Resilience

Resilience of water resources systems is its capacity to adapt to changing conditions (WHO, 2009). The ‘resilience’ of a time series is defined as the probability that if time series variable at any time is in an unsatisfactory (failure) state, the next state will be satisfactory (successful). In other words, it is the probability of having a satisfactory value or successful event in time period  $t-1$ , given an unsatisfactory value or failure event in any time period  $t$ . It can be expressed as (Machiwal and Jha, 2012):

$$R_e = f_{FE-SE} / f_{FE} \quad (2)$$

Where,  $R_e$  = resilience of time series;  $f_{FE-SE}$  = number of times a satisfactory value (successful event) follows an unsatisfactory value (failure event); and  $f_{FE}$  = number of times an unsatisfactory value occurs in the time series.

### 2.4.3 Vulnerability

Vulnerability is the likely value of deficits, if they occur (Hashimoto et al., 1982). The term ‘vulnerability’ is a measure of the extent of the differences between the threshold value and the failure events among rainfall time series data. Obviously, this is a probabilistic measure, which is also known as expected values, maximum observed values, and probability of exceedance to vulnerability measures. Assuming an expected value measure of vulnerability is to be used, vulnerability of the rainfall time series can be expressed as follows (Machiwal and Jha, 2012):

$$V_y = \sum_{i=1}^n \text{difference}(x^T - x_t) / f_{FE} ; t = 1, 2, \dots n \quad (3)$$

Where,  $V_y$  = vulnerability of rainfall time series; and  $\sum_{i=1}^n \text{difference}(x^T - x_t)$  = sum of positive values of  $(x^T - x_t)$ .

In this study, the rainfall vulnerability was divided by threshold mean rainfall such that value of rainfall vulnerability ranges between 0 and 1.

#### 2.4.4 Sustainability Index

Sustainability index was originally developed by Loucks (1997) to quantify sustainability of water resources systems in order to facilitate the evaluation and comparison of water management policies. The sustainability index (SI) in multiplicative form is expressed below (Loucks, 1997).

$$SI = R_v \times R_e \times (1 - V_y) \quad (4)$$

The SI values vary from 0-1; if one of three performance parameters is zero, the sustainability will also be zero. There is an implicit weighting because the index gives added weight to the worst to the criteria with the worst performance.

### 3. RESULTS AND DISCUSSION

#### 3.1 Basic Statistics of Rainfall Time Series

Salient statistical properties and time plots of the annual rainfall time series of ten rainfall stations are presented in Table 1 and Fig. 2, respectively. It is seen that the mean annual rainfall is highest (479 mm) for Mundra station whereas, it is the lowest (323 mm) for Dayapar station. Standard deviation is the maximum (340 mm) for Mandvi and the minimum (236 mm) for Gandhidham rainfall station. It is also evident that annual rainfall series are positively-skewed for all the stations (Table 1). Also, skewness coefficients are comparatively higher for Mandvi and Dayapar stations than that for other stations, indicating more low values than high values. There are wide variations in annual rainfall series of all the stations as coefficient of variation (CV) values are more than 50% with relatively large

variations for Mandvi station (CV=80%). It is well discernible from Fig. 2 that time pattern of annual rainfall series for most of the stations is not exactly similar. In years 1994 and 2010, the relatively heavy annual rainfall at most stations significantly deviated from the mean annual rainfalls (annual rainfall exceeded mean plus standard deviation). It is evident from Fig. 2 that such high-magnitude annual rainfall is occurring at relative high frequency after the year 2000. Before the year 2000, heavy rainfall at many rainfall stations was experienced four times during the years 1988, 1992, 1994 and 1997 over 21-year span. On the other side, heavy rainfall at most stations occurred four times over 13-year (2001-2013) period including two recent years, i.e. 2011 and 2013.

### **3.2 Presence/Absence of Normality in Rainfall**

Box-whisker plots of the annual rainfall series are shown in Fig. 3. It is observed that value of the median rainfall is the lowest (273 mm) for Dayapar station while the maximum median rainfall (464 mm) occurred at Mundra station. It is seen from Fig. 3 that the annual rainfall medians of Naliya, Anjar, Bhachau, Dayapar, Mundra, Nakhatrana and Rapar are situated at the centre of box between the upper and lower quartiles, which indicate uniform or normal distribution of the rainfall series. However, the median rainfall of Bhuj, Gandhidham and Mandvi stations is closed to the lower quartile. Furthermore, few mild outliers can be seen in annual rainfall series of Anjar, Bhachau, Dayapar, Nakhatrana and Rapar stations. In addition, one severe outlier and one extreme value can be seen in annual rainfall series of Mandvi and Dayapar stations, respectively (Fig. 3). Presence of the severe outlier and extreme at Mandvi and Dayapar stations makes the rainfall series positively-skewed.

One of the significant observations of box-whisker plots is the presence of mild outliers and extreme in annual rainfalls of six rainfall stations. Normal probability plots, drawn to confirm findings of box-whisker plots and to test normality, are shown in Figs. 4(a-j). Fig. 4 shows that a straight line cannot be obtained for annual rainfall series of Bhachau, Dayapar and Mandvi station; otherwise, annual rainfall time series of rest seven rainfall stations do not largely deviate from the straight line. Presence of the non-normality in annual rainfall series of Bhachau is attributed to presence of four mild outliers. Similarly, presence of extreme and severe outlier at Dayapar and Mandvi stations, respectively makes the annual rainfall time series non-normal in nature.

Histograms of the annual rainfall series for ten stations are shown in Figs. 5(a-j). It is apparent from Figs. 5(a-j) that distribution of rainfall for six stations, i.e. Naliya, Anjar, Gandhidham, Mundra, Nakhatrana and Rapar, approximately, follows a normal distribution. However, rainfall histograms of Bhachau, Bhuj, Dayapar and Mandvi stations [Fig. 5(c,d,f,g)] reveal slight deviation from the normal distribution. Presence of four mild outliers in rainfall series of Bhachau, one extreme for Dayapar, and one severe outlier for Mandvi station [Fig. 5(g)] significantly contributes to non-normality and positive skewness of the rainfall time series as discussed earlier.



Observed test-statistics, i.e. SW-W, D and Lilliefors-p of three normality tests, i.e. Shapiro-Wilk (S-W) test, Kolmogorov-Smirnov (K-S) test and Lilliefors test, respectively are shown in Figs. 4(a-j) along with p-values. In results of S-W test, if  $p\text{-value} > 0.01$ , then null hypothesis of presence of normality cannot be rejected at 1% level of significance (l.s.). Thus, annual rainfall of seven rainfall stations (Naliya, Anjar, Bhuj Gandhidham, Mundra, Nakhatrana and Rapar) is considered to be normal ( $p\text{-value} > 0.01$ ) based on S-W test. However, annual rainfall series of Bhachau, Dayapar and Mandvi slightly deviates from normality ( $p\text{-value} < 0.01$ ). Results of the K-S test indicate that null hypothesis of presence of normality cannot be rejected at 5% l.s. for any of the rainfall stations. Results of Lilliefors test show that annual rainfall series of Bhachau and Dayapar stations does not follow the normal distribution ( $p < 0.01$ ). It is clearly revealed from this discussion that stations showing normality/non-normality of annual rainfall series do not exactly match but differ depending on the normality tests applied in this study. This finding justifies the use of multiple statistical tests (more than two) to detect time series characteristics.

It is worth-mentioning that the K-S test is strongly criticized by the researchers due to ambiguous results (Steinskog et al., 2007), particularly, results of not rejecting normality could be very misleading. Therefore, the results of the Lilliefors test and S-W test are preferred over the K-S test in this study, which indicate that slight non-normality is present in rainfall series of Bhachau and Dayapar stations.

### 3.3 Stationarity in Annual Rainfall

Results of stationarity tests are shown in Table 2. For applying stationarity tests, the rainfall series of every station was divided into two sub-series, i.e. first half and second half of the whole series. Calculated t-statistic of Student's t-test is the lowest (0.123) for Dayapar rainfall station for both the sub-series (Table 2), which indicates comparatively more chances of the annual rainfall series of this station to be stationary. On the other hand,  $t_{\text{calculated}}$  for the annual rainfall of Gandhidham and Rapar rainfall stations are comparatively high, i.e. 1.139 and 1.88, respectively, indicating relatively lesser chances for presence of stationarity in the rainfall time series. On comparing  $t_{\text{calculated}}$  with its critical value, it can be seen that  $t_{\text{calculated}}$  are less than their critical values for all the rainfall stations except for Rapar station where  $t_{\text{calculated}} > t_{\text{critical}}$  (Table 2); the null hypothesis of presence of stationarity in the rainfall time series of Rapar station is to be rejected at 5% l.s.

Comparison of computed ( $t_{\text{computed}}$ ) and critical ( $t_{\text{critical}}$ ) test-statistic values of Simple t-test indicate that  $t_{\text{computed}} > t_{\text{critical}}$  for annual rainfall series of Gandhidham and Rapar stations. This suggests that null hypothesis is to be rejected at 5% l.s., and hence, the rainfall of these two stations is non-stationary. Absence of stationarity in annual rainfall of Gandhidham station may be due to relatively lesser size of the time series, i.e. 16 years. Further, results of the Mann-Whitney test support the findings of Student's t-test as  $u_{\text{computed}} < u_{\text{critical}}$  for all the

stations except for the Rapar station where null hypothesis of presence of stationarity is to be rejected at 5% l.s. (Table 2). Overall, considering the robust nature of the nonparametric test (Machiwal and Jha, 2012) and looking at similar findings of majority of the tests (Student's t-test and Mann-Whitney test) in this study, non-stationarity is present in the annual rainfall series of Rapar station.

### 3.4 Homogeneity of Rainfall Time Series

Results of four homogeneity tests are summarized in Table 3. Observed difference of Tukey test for annual rainfall of nine stations is less than its critical limit,  $W$  (Table 3); annual rainfall series of Rapar station is statistically non-homogeneous as observed difference is more than  $W$ . This indicates that except single rainfall series, annual rainfall of rest nine stations is statistically homogeneous.

In case of Link-Wallace test, it can be seen from Table 3 that values of  $K_L$  are statistically non-significant ( $K_L < K_{critical}$ ) at 5% l.s. for nine rainfall stations; but for Rapar rainfall station, annual rainfall time series is statistically non-homogeneous as  $K_L > K_{critical}$  (Table 3). The results of the Bartlett test (Table 3) indicate presence of homogeneity in annual rainfall time series for eight of the total ten rainfall stations as values of the observed test-statistic ( $B_{computed}$ ) are less than their critical values ( $B_{critical}$ ) at 5% l.s.; non-homogeneity is present in annual rainfall series of Rapar and Dayapar stations ( $B_{computed} > B_{critical}$ ). The results of Hartley test reveal that the observed test-statistic ( $F_{max}$ ) values are greater than their critical values ( $F_{critical}$ ) for annual rainfall of single station, i.e. Rapar (Table 3), which are in agreement with findings of the Tukey test and Link-Wallace test. The annual rainfall of rest nine rainfall stations is homogeneous based on results of the Hartley test.

It is evident from the above discussion that the results of three homogeneity tests revealed non-homogeneity in annual rainfall time series of Rapar station only. However, results of Bartlett test indicated that non-homogeneity is associated with annual rainfall of two rainfall stations, i.e. Rapar and Dayapar. These findings further justify the approach of using multiple statistical tests (at least two) for detecting characteristics of rainfall time series in this study.

### 3.5 Trends in Annual Rainfall

Results of the regression test for rainfall time series of ten stations are presented in Figs. 6(a-j) where rainfall barcharts along with fitted linear model (shown by dotted line), model equation and value of goodness-of-fit criterion, i.e. coefficient of determination ( $R^2$ ) are shown. It is revealed from the fitted regression models shown in Fig. 6 that an overall increasing trend of varying magnitudes exists in annual rainfall time series of nine stations; however, fitted trend line is almost flatter/horizontal in case of rainfall of Dayapar station and the slope of the fitted line with respect to horizontal year axis is the least for Mundra, Naliya and Nakhatrana stations. On the other side, the slope of the fitted trend line looks to be the highest for annual rainfall series of Gandhidham, Rapar, Mandvi and Bhachau stations. The

$R^2$  values of the trend line is comparatively low for Dayapar ( $R^2=0.0048$ ), Mundra ( $R^2=0.0124$ ) and Naliya ( $R^2=0.0186$ ) stations and relatively high for Rapar ( $R^2=0.3025$ ), Gandhidham ( $R^2=0.2833$ ), Bhachau ( $R^2=0.1251$ ) and Mandvi ( $R^2=0.087$ ) stations.

Results of three nonparametric trend tests are summarized in Table 4. It is clearly seen from Table 4 that calculated test-statistic values of SROC test are less than their critical values (1.694) for annual rainfall series of seven stations (Naliya, Anjar, Bhuj, Dayapar, Mandvi, Mundra and Nakhatrana), and this finding suggests that the annual rainfall of these stations does not have any linear trends. However, calculated test-statistic values of the SROC test for rest three rainfall stations, i.e. Bhachau, Gandhidham and Rapar, are greater than their critical values at 5% l.s., indicating presence of a significant trend in annual rainfall series. Furthermore, results of KRC test indicate presence of statistically-significant trend in annual rainfall series of two stations (Gandhidham and Rapar) as calculated test-statistic values are greater than their critical values ( $\pm 1.96$ ) at 5% l.s. (Table 4); annual rainfall time series of rest eight stations are trend-free. It is obvious from Table 4 that results of the M-K test are in close agreement with those of the KRC test, which highlights the equal competence of both the tests in detecting trends in hydrological time series. Similar findings have been reported in earlier studies also (e.g. Machiwal and Jha, 2008).

Based on above discussion, it is inferred that the parametric test revealed considerable increasing trend in annual series of four stations, i.e. Rapar, Gandhidham, Bhachau and Mandvi. However, results of the SROC test suggests significant trend only in three of the earlier detected four stations, i.e. Bhachau, Gandhidham and Rapar. Furthermore, results of the two most powerful and widely-used trend detection tests, i.e. KRC test and MK test, indicate statistically-significant rising trend in annual series of only two stations, i.e. Rapar and Gandhidham. These findings further explain the importance of using multiple statistical tests' approach employed in this study.

### **3.6 Persistence**

Autocorrelograms for annual rainfall of ten rainfall stations are shown in Figs. 7(a-j). Depending upon the length (34 years) of rainfall time series, autocorrelation coefficients/functions were computed up to a maximum order of 9 years. The upper and lower bounds of the acceptable or non-critical region were delineated by the Anderson's test (Anderson, 1942). It is discernible from Fig. 7 that pattern of the rainfall autocorrelograms is similar for rainfall series of eight stations (Naliya, Anjar, Bhachau, Bhuj, Dayapar, Mandvi, Mundra and Nakhatrana) though the individual autocorrelograms have random movement closer to zero over the time lag scale. The autocorrelograms for two stations (Gandhidham and Rapar) have time patterns differing from those of other stations. The different pattern of autocorrelograms for Gandhidham is due to comparatively small-size dataset (16 years). It is apparent from Fig. 7 that values of autocorrelation function at any time lag are within the acceptable or non-critical region for six stations, i.e. Naliya, Anjar, Bhuj, Gandhidham,

Dayapar and Mandvi. This indicates that annual rainfall of these six stations is non-persistent. However, rainfall autocorrelograms cross the non-critical region for Bhachau (at time lag of 3 years), Mundra (time lag of 1 and 9 years), Nakhatrana (time lag of 9 years), and Rapar (time lag of 3 and 4 years) stations, indicating presence of persistence in rainfall series. Further, the deviations of autocorrelation function from the upper and lower critical limits seem to be insignificant for Bhachau (0.02), Mundra (-0.04 and 0.03), Nakhatrana (0.21) and Rapar (0.03 and 0.04) stations for practical purposes.

### **3.7 Sustainability of Annual Rainfall**

Results of sustainability analysis of annual rainfall time series for the nine rainfall stations are presented as barcharts of reliability, resilience and vulnerability in Fig. 8; Gandhidham station was excluded from rainfall sustainability analysis due to comparatively lesser size of the dataset. In this study, threshold value was considered as the overall mean annual rainfall for the study area, which is 326 mm. Also, a successful (or failure) event was considered when rainfall in a year exceeded (or did not exceed) the threshold annual rainfall of the study area.

#### **3.7.1 Reliability of Rainfall Series**

It is apparent from Fig. 8 that reliability value ( $R_y$ ) for annual rainfall is less than 0.50 for all the stations. Thus, less than half of the total data exceed the mean annual rainfall in 34-year rainfall time series of a station. In other words, it suggests that there are more values lower than mean in the rainfall series compared to that higher than the mean. The low  $R_y$  values indicate that annual rainfall in the study area is relatively less reliable. In the study area,  $R_y$  values of Mundra and Mandvi rainfall stations are comparatively higher (approaching 0.50) than that of the other stations (Fig. 8). However, the reliability of annual rainfall is the least ( $R_y \leq 0.35$ ) for Bhachau and Dayapar stations, and low-to-moderate ( $0.35 < R_y < 0.45$ ) for Naliya, Anjar, Bhuj, Nakhatrana and Rapar rainfall stations.

#### **3.7.2 Resilience of Rainfall Series**

It is observed from Fig. 8 that resilience of the annual rainfall is less than 0.50 for all the stations. This means less than half of times a successful event (annual rainfall more than the overall mean) follows occurrence of a failure event (annual rainfall less than the overall mean) at any of the stations over a period of 34-years. Thus, the annual rainfall series of the study area are relatively less adaptable to changing conditions. The annual rainfall is the most resilient (with maximum  $R_e = 0.47$ ) for two stations, i.e. Naliya and Mundra (Fig. 8). On the contrary, the annual rainfall series of Dayapar station is the least resilient with  $R_e$  value of 0.32. The resilience of annual rainfall for rest six rainfall stations (Anjar, Bhachau, Bhuj, Mandvi, Nakhatrana and Rapar) is low to moderate ( $0.40 \leq R_e \leq 0.45$ ).

#### **3.7.3 Vulnerability of Rainfall Series**

It is depicted from Fig. 8 that vulnerability of annual rainfall is less than 0.50 at seven of the nine stations, which indicate that deficit in the annual rainfall are relatively less-likely to occur in the study area. The vulnerability of the annual rainfall is the lowest for Bhachau and Rapar stations ( $V_y=0.36$  and  $0.37$ , respectively), whereas the annual rainfall of Mandvi and Bhuj rainfall stations is highly vulnerable ( $V_y=0.59$  and  $0.51$ , respectively) compared to that at rest of the stations (Fig. 8).

### 3.7.4 Sustainability Index of Rainfall Series

An interesting finding of sustainability approach is the lowest vulnerability for annual rainfall of Bhachau rainfall station ( $V_y=0.36$ ), which is the least reliable ( $R_y=0.32$ ) and moderately resilient ( $R_e=0.43$ ). Similar to annual rainfall of Bhachau station, annual rainfall of Rapar rainfall station is relatively less vulnerable ( $V_y=0.37$ ) over the 34 years despite the fact that rainfall of this station is comparatively less reliable ( $R_y=0.38$ ) and resilient ( $R_e=0.43$ ). The most sustainable rainfall time series, as revealed from Fig. 8, is of the Mundra rainfall station ( $R_y=0.50$ ;  $R_e=0.47$ ;  $V_y=0.49$ ) followed by Naliya station ( $R_y=0.44$ ;  $R_e=0.47$ ;  $V_y=0.46$ ). Thus, annual rainfall of Mundra and Naliya rainfall stations is more dependable and sustainable compared to rainfall of other stations in the study area.

Furthermore, it is revealed from Fig. 8 that the sustainability index for the annual rainfall ranges from 0.061 for Dayapar station to 0.12 for Mundra station. The two most sustainable rainfall series were found at Mundra ( $SI=0.12$ ) and Naliya ( $SI=0.112$ ) stations. These findings are in agreement with earlier based on combined  $R_y$ ,  $R_e$  and  $V_y$  criteria. The order of decreasing sustainability of the annual rainfall in the study area is observed as Mundra>Naliya>Anjar>Rapar>Nakhatrana>Bhachau>Mandvi>Bhuj>Dayapar. Thus, the least sustainable rainfall time series is found at Mandvi, Bhuj and Dayapar stations. Looking at the least sustainability of the rainfall, relatively high priority for the water resources management is inevitable at these stations.

In order to compare the three performance indicators of the sustainability, i.e. reliability, resilience and vulnerability, along with sustainability index for the annual rainfall series of nine stations in the study area, box-whisker plots were drawn, which are shown in Fig. 9. It is clearly seen that the resilience of the rainfall has the least variability among three performance criteria over the area, whereas, the vulnerability is the highly variable over the space. The median values of the reliability, resilience, vulnerability and sustainability index are 0.41, 0.44, 0.46 and 0.10, respectively. Hence, in general, the annual rainfall of the area is little less reliable, less resilient and moderately vulnerable, which emphasizes need of managing water resources of the area adequately to meet both domestic and agricultural demands in case of failure of monsoon.

## 4. CONCLUSIONS

Present study aimed at characterizing rainfall of arid region of Gujarat, India at annual time scale by using time series modelling techniques and sustainability approach. Every characteristic of 34-year rainfall time series, i.e. normality, stationarity, homogeneity, presence/absence of trend, and persistence for ten rainfall gauging stations of Kachchh district was evaluated by applying multiple statistical tests, both parametric and nonparametric in nature. The novelty of this study involves proposing concept of sustainability for evaluating rainfall time series and identifying sustainable and dependable rainfall time series by using R-R-V (reliability, resilience and vulnerability) approach.

Annual rainfall time series of all the stations is observed to be positively-skewed with relatively high skewness for Mandvi and Dayapar stations. Coefficient of variation for rainfall is relatively high for Mandvi station. Box-whisker plots revealed presence of one severe outlier and one extreme in rainfall series of Mandvi and Dayapar stations, respectively. The normal probability plots and histograms indicated slightly non-normality in Bhachau, Mandvi and Dayapar stations due to presence of outlier/extreme. Results of the powerful statistical normality tests, i.e. Lilliefors test and Shapiro-Wilk test confirmed the presence of slight non-normality in rainfall series of Bhachau and Dayapar stations. Results of the two parametric and one nonparametric Mann-Whitney test suggested that annual rainfall time series of Rapar station is non-stationary. The annual rainfall time series of Rapar station is also found non-homogeneous based on the four parametric homogeneity tests. Results of the one parametric and three nonparametric trend detection tests, applied in this study, revealed that significantly increasing trends exist in annual rainfall time series of two stations, i.e. Rapar and Gandhidham. The significant trend in rainfall series of Gandhidham station may be due to relatively lesser size of the rainfall datasets, i.e. 16 years. Autocorrelation analysis indicated almost similar time patterns of autocorrelation functions for eight rainfall stations, however, the time patterns for two stations, i.e. Gandhidham and Rapar, were different from those of other eight stations. In case of Gandhidham rainfall station, different time pattern of autocorrelogram is due to comparatively lesser size of rainfall datasets. The autocorrelation analysis revealed persistence in annual rainfall time series of four stations, i.e. Bhachau, Mundra, Nakhatrana, and Rapar with time lag of 3, 1 and 9, 9, and 3 and 4 years, respectively. However, such persistence is found to be non-significant for practical purposes. Results of sustainability concept based on R-R-V approach suggested that the most sustainable and dependable annual rainfall time series is for two stations, i.e. Mundra ( $R_y=0.50$ ;  $R_e=0.47$ ;  $V_y=0.49$ ) and Naliya ( $R_y=0.44$ ;  $R_e=0.47$ ;  $V_y=0.46$ ). The sustainability index values for annual rainfall series of Mundra and Naliya were observed to be the highest, i.e. 0.12 and 0.112, respectively, which confirmed the earlier findings. In general, little less reliable, less resilient and moderately vulnerable rainfall of the study area suggests necessity of adopting suitable measures for efficient management of scanty water resources to meet escalating water demands during drought years.

Finally, it is emphasized that approach of using multiple statistical tests (at least two) to detect the similar time series characteristic is very useful to arrive at vital decision. In

addition, novel application of R-R-V approach is successfully demonstrated for analyzing rainfall sustainability and dependability in the Indian arid region. Methodology adopted in this study may easily be applied and findings may be useful for other arid regions worldwide.

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Table 1. Salient statistical properties of annual rainfall time series for ten rainfall stations of Kachchh district

Statistical Property	Rainfall Station									
	Naliya	Anjar	Bhachau	Bhuj	Gandhidham	Dayapar	Mandvi	Mundra	Nakhatrana	Rapar
Mean (mm)	379	384	400	353	406	323	405	479	381	407
Standard Deviation (mm)	243	238	258	246	236	276	340	288	262	248
Skewness	0.60	0.82	1.16	0.56	0.45	1.71	1.81	0.35	0.84	1.01
Kurtosis	-0.40	0.25	0.78	-0.84	-0.75	3.44	5.24	-0.35	0.38	0.65
Coefficient of Variation (%)	59	56	65	67	58	64	80	51	59	56

Table 2. Comparison of observed and critical test-statistics for the t-test and Mann-Whitney test applied to ten rainfall time series of Kachchh

Rainfall Station	Student t-test			Simple t-test		Mann-Whitney Test	
	$t_{\text{calculated}}$		$t_{\text{critical}}$	$t_{\text{computed}}$	$t_{\text{critical}}$	$u_{\text{computed}}$	$u_{\text{critical}}$
	first-half	second-half					
Naliya	-0.335	0.335	1.746	0.51	1.694	-0.60	$\pm 1.96$
Anjar	-0.889	0.889	1.746	1.31	1.694	-1.46	$\pm 1.96$
Bhachau	-1.062	1.062	1.746	1.58	1.694	-1.67	$\pm 1.96$
Bhuj	-0.654	0.654	1.746	0.95	1.694	-1.12	$\pm 1.96$
Gandhidham	-1.139	1.139	1.895	<b>1.86</b>	1.761	-1.89	$\pm 1.96$
Dayapar	0.123	-0.123	1.746	0.18	1.694	-0.50	$\pm 1.96$
Mandvi	-0.846	0.846	1.746	1.24	1.694	-1.29	$\pm 1.96$
Mundra	-0.497	0.497	1.746	0.72	1.694	-0.98	$\pm 1.96$
Nakhatrana	-0.562	0.562	1.746	0.81	1.694	-1.26	$\pm 1.96$
Rapar	<b>-1.880</b>	<b>1.880</b>	1.746	<b>3.07</b>	1.694	<b>-2.67</b>	$\pm 1.96$

Note: Figures in bold face indicate the rejection of the null hypothesis of normality.

Table 3. Observed and critical test-statistics of homogeneity tests for annual rainfall time series of ten rainfall stations of Kachchh

Rainfall Station	Tukey Test		Link-Wallace Test		Bartlett Test		Hartley Test	
	Observed Difference	Critical Limit, W	$K_L$	$K_{critical}$	$B_{computed}$	$B_{critical}$	$F_{max}$	$F_{critical}$
Naliya	43.2	171.9	0.44	1.66	0.45	3.84	1.40	2.03
Anjar	105.8	164.4	1.00	1.66	0	3.84	1.00	2.03
Bhachau	137.1	176.4	1.25	1.66	0.19	3.84	0.80	2.03
Bhuj	80.4	172.1	0.85	1.66	0	3.84	0.97	2.03
Gandhidham	202.9	234.2	1.24	1.49	0.65	3.84	1.86	2.86
Dayapar	16.9	195.5	-0.14	1.66	<b>4.10</b>	3.84	<b>2.83</b>	2.03
Mandvi	143.8	235.7	0.92	1.66	0.55	3.84	0.69	2.03
Mundra	71.59	202.7	0.60	1.66	1.07	3.84	1.69	2.03
Nakhatrana	73.59	184.0	0.66	1.66	1.06	3.84	1.68	2.03
Rapar	<b>232.82</b>	154.5	<b>2.51</b>	1.66	<b>4.15</b>	3.84	0.35	2.03

**Note:** Figures in bold face indicate the rejection of the null hypothesis of homogeneity.

Table 4. Calculated and critical test-statistic values of trend tests for the annual rainfall time series

Rainfall Station	Spearman Rank Order Correlation Test		Kendall Rank Correlation Test		Mann-Kendall Test	
	Calculated	Critical <sup>a</sup>	Calculated	Critical <sup>a</sup>	Calculated	Critical <sup>a</sup>
Naliya	0.72	1.694	0.58	±1.96	0.58	±1.96
Anjar	1.62	1.694	1.92	±1.96	1.60	±1.96
Bhachau	<b>1.74</b>	1.694	1.73	±1.96	1.72	±1.96
Bhuj	1.11	1.694	1.11	±1.96	1.11	±1.96
Gandhidham	<b>2.70</b>	1.761	<b>2.25</b>	±1.96	<b>2.21</b>	±1.96
Dayapar	0.77	1.694	0.67	±1.96	0.65	±1.96
Mandvi	1.62	1.694	1.76	±1.96	1.75	±1.96
Mundra	0.79	1.694	0.76	±1.96	0.74	±1.96
Nakhatrana	1.13	1.694	1.02	±1.96	1.02	±1.96
Rapar	<b>3.45</b>	1.694	<b>3.04</b>	±1.96	<b>3.04</b>	±1.96

Note: \*  $p < 0.05$ ; <sup>a</sup> Critical values are at  $\alpha = 0.05$ .

## Figure Captions

- Fig. 1. Location map of Kachchh, Gujarat showing locations of rainfall stations in ten blocks
- Fig. 2. Line diagram of annual rainfall series showing temporal distribution of the rainfall along with mean  $\pm$  standard deviation (SD) over 34-year period (1980-2013) for the ten rainfall stations
- Fig. 3. Box and whisker plots of 34-year annual rainfalls depicting presence of normality/non-normality at ten rainfall stations
- Fig. 4. Normal probability plots showing deviation of annual rainfall from normal distribution for ten rainfall stations
- Fig. 5. Histograms along with test-statistic values of Shapiro-Wilk (SW-W), Kolmogorov-Smirnov (D) and Lilliefors normality tests indicating normal/non-normal annual rainfall time series based on significant and non-significant (n.s.) p-values
- Fig. 6. Barcharts of annual rainfall showing presence of linear trend, its equation (x as year on abscissa and y as annual rainfall on ordinate) and coefficient of determination ( $R^2$ ) values
- Fig. 7. Autocorrelograms for annual rainfall time series showing presence of significant persistence in annual rainfall series of ten stations in the study area
- Fig. 8. Barcharts of reliability, resilience, vulnerability and sustainability index for 34-year annual rainfall series of nine rainfall stations
- Fig. 9. Box-whisker plots indicating comparative spatial variability of reliability ( $R_y$ ), resilience ( $R_e$ ), vulnerability ( $V_y$ ) and sustainability index (SI) of annual rainfall in the study area

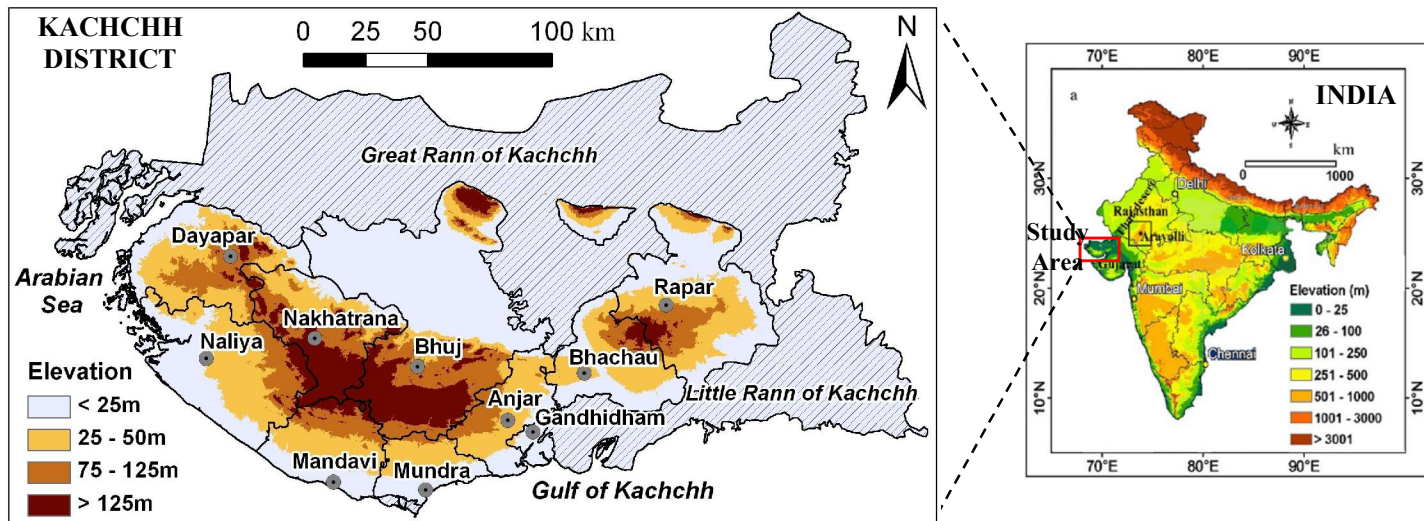


Figure 1

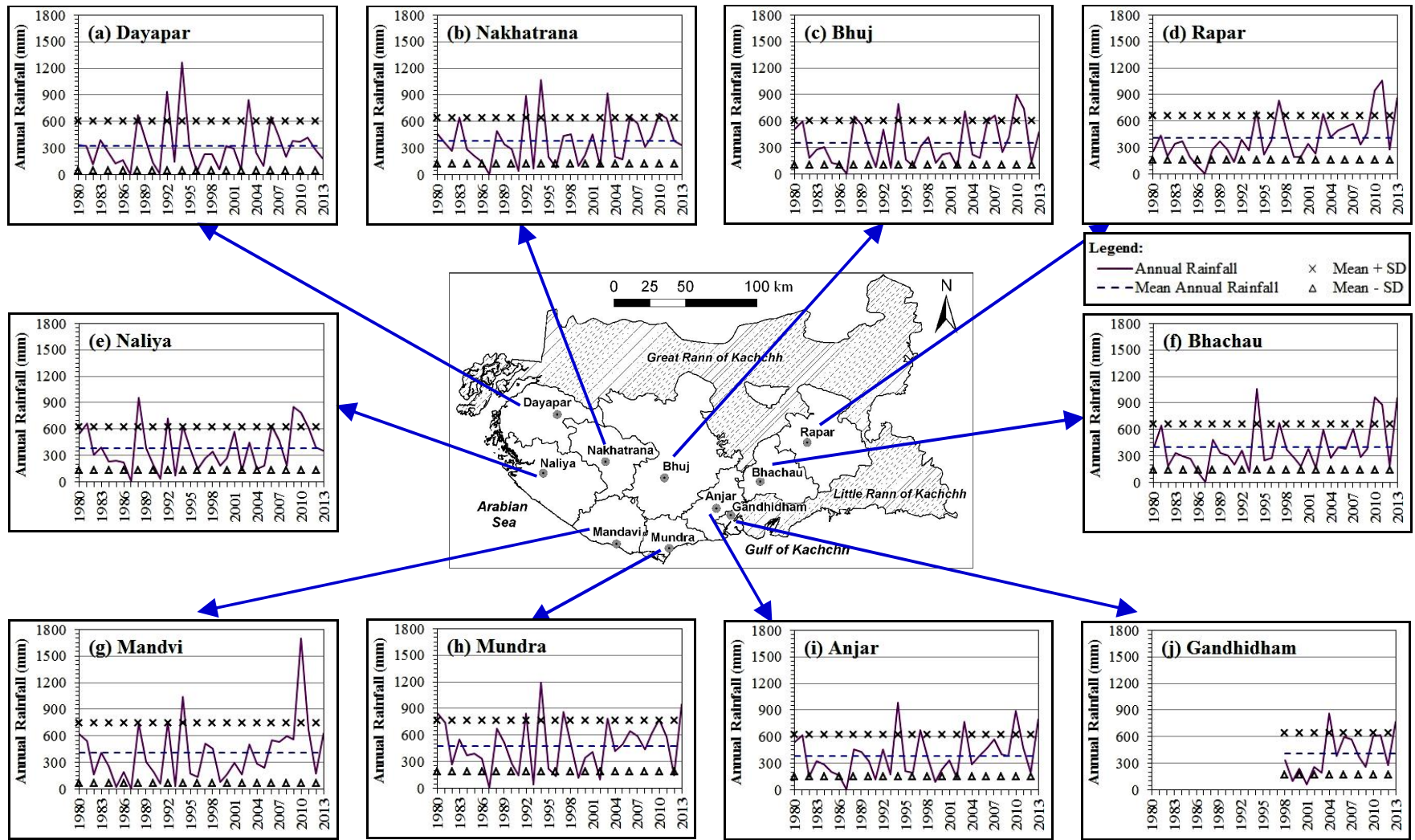


Figure 2



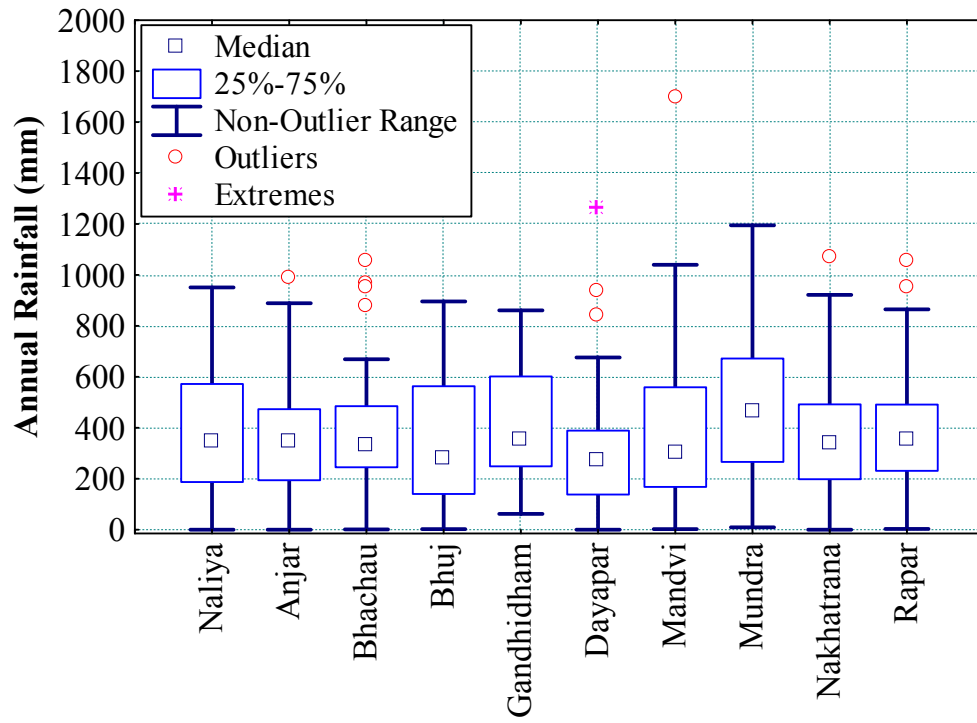


Figure 3

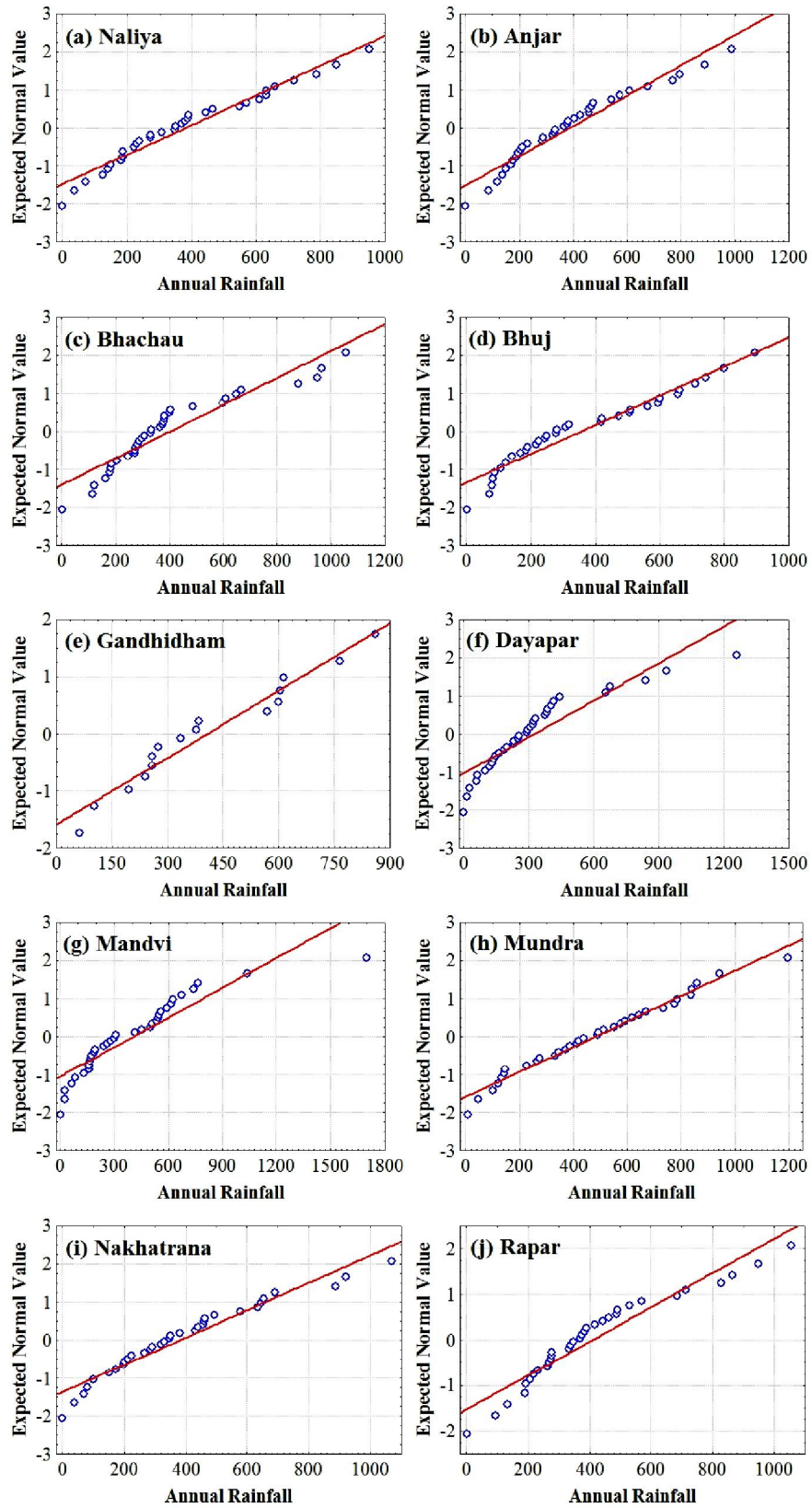


Figure 4

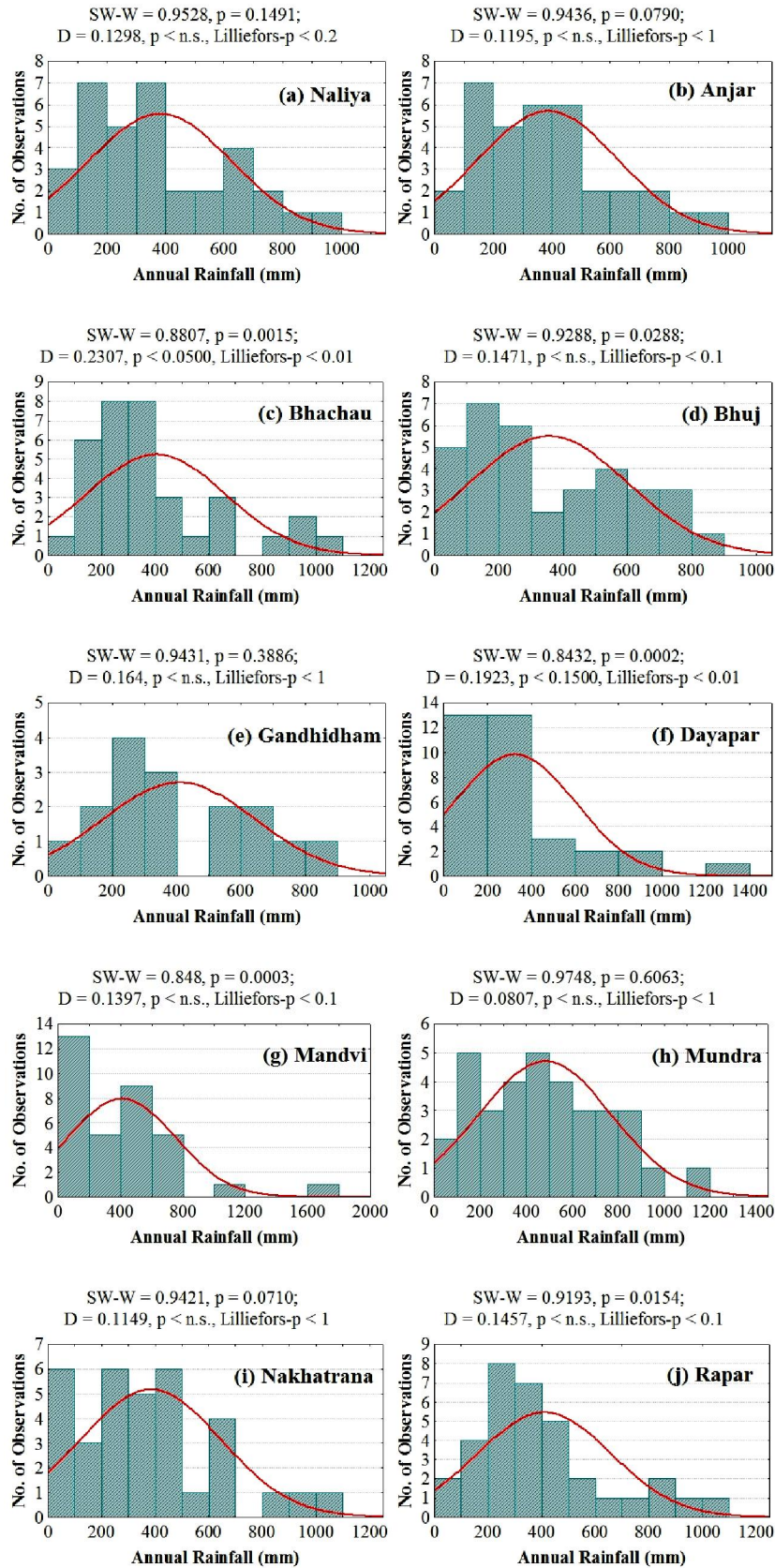


Figure 5

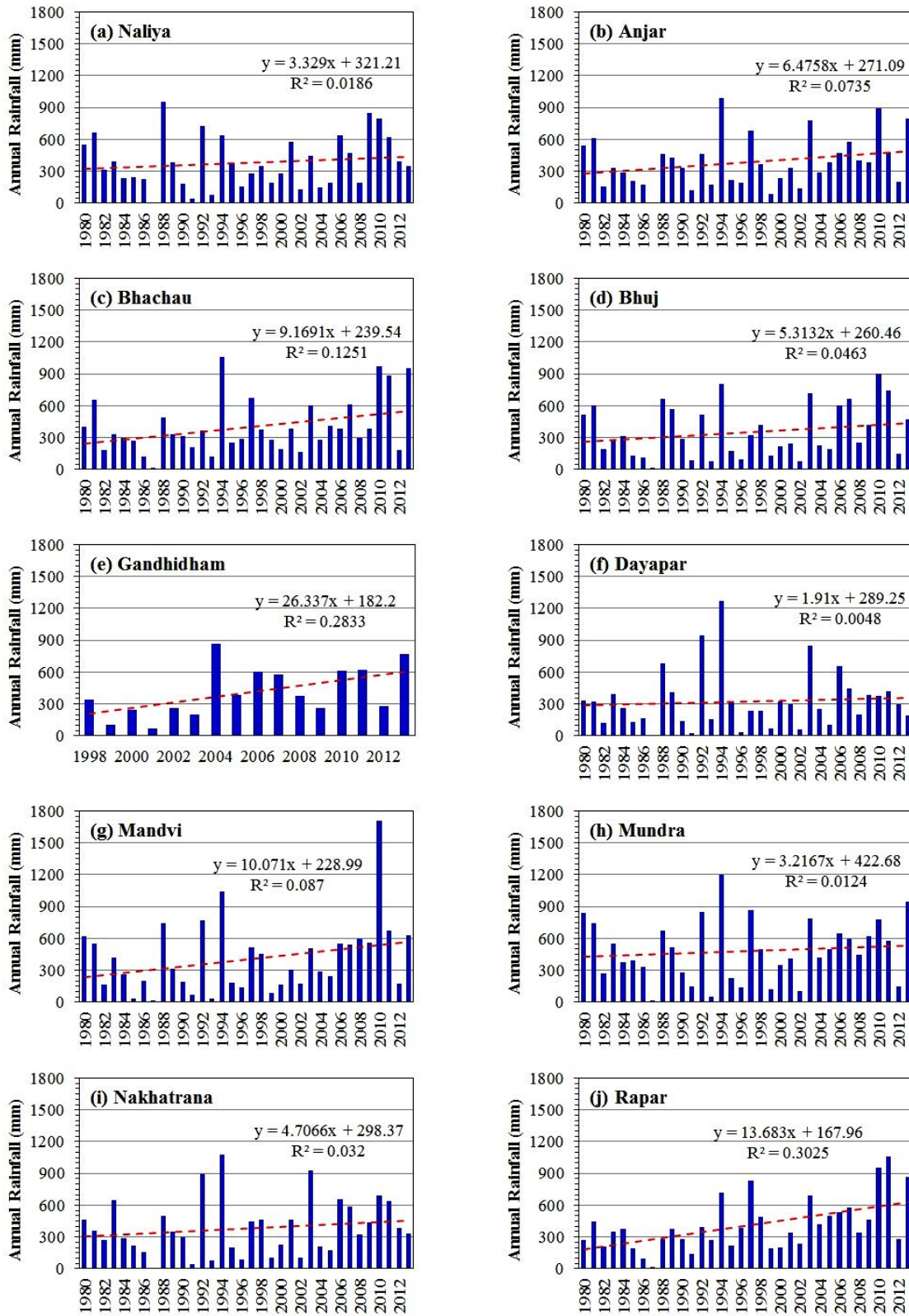


Figure 6

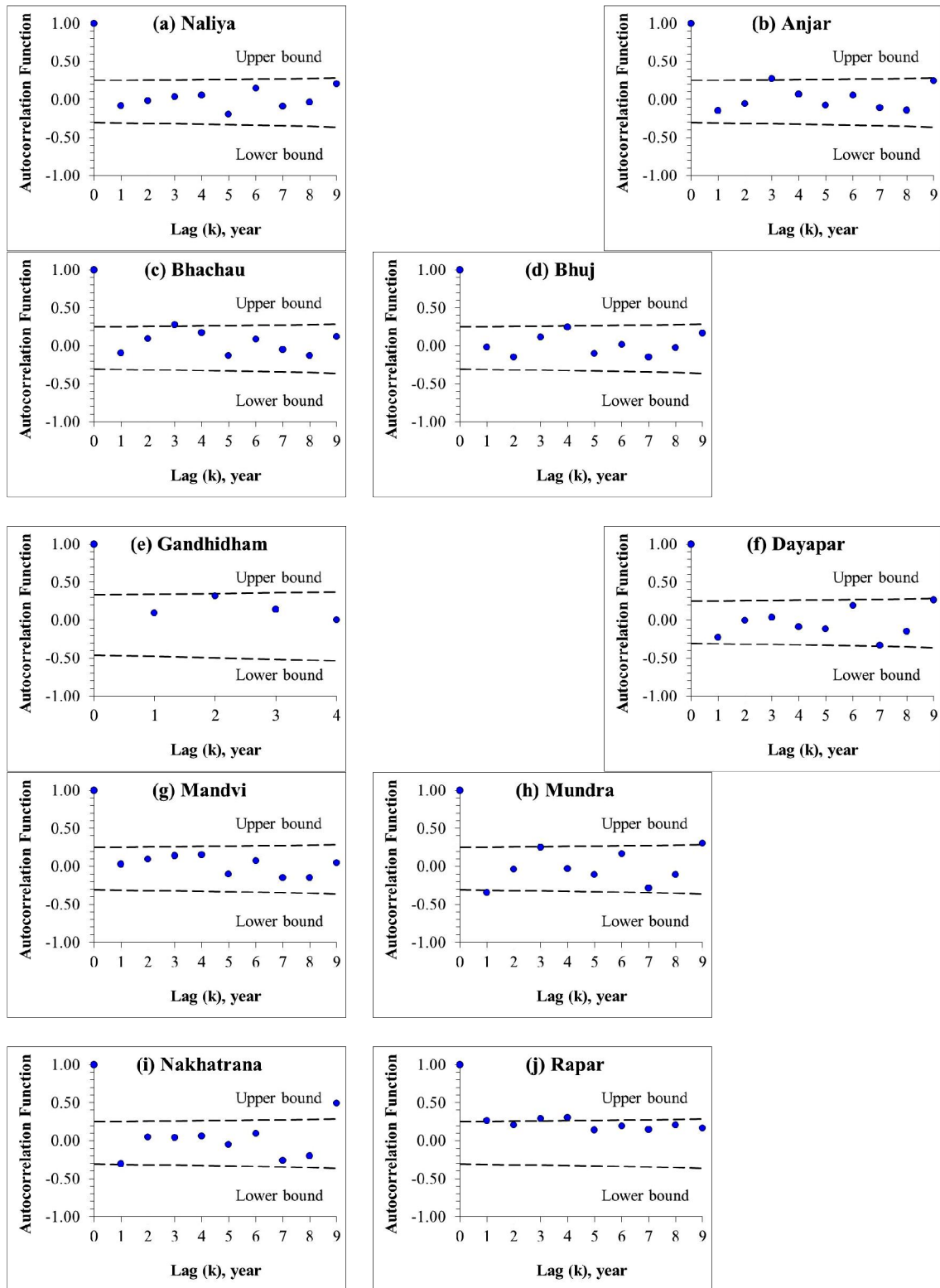


Figure 7

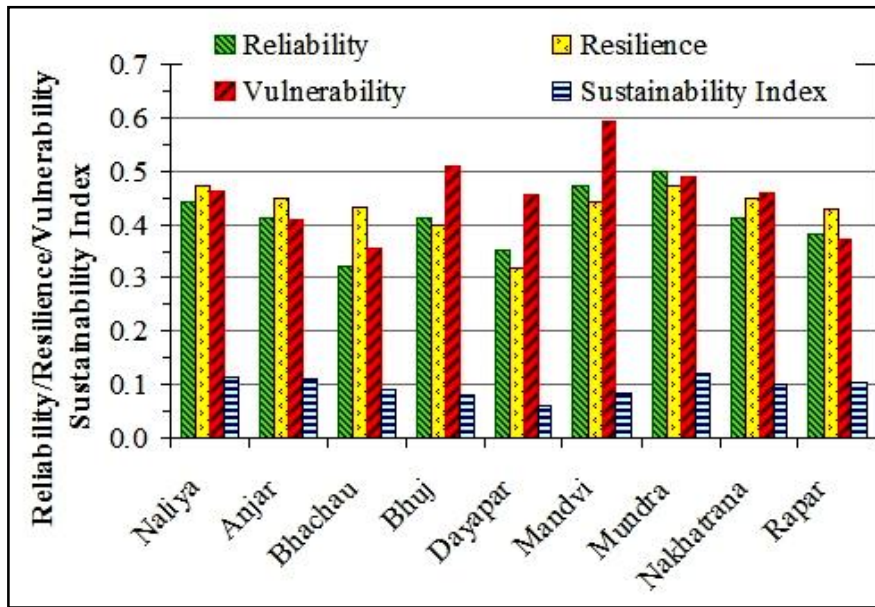


Figure 8

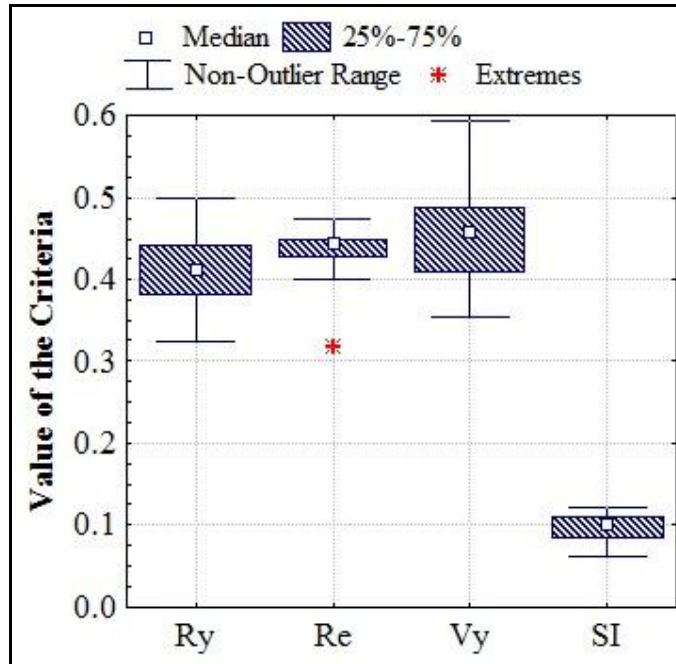


Figure 9