Temporal Variability of Climatic Parameters of Yamuna River Basin: Spatial Analysis of Persistence, Trend and Periodicity

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Abstract: Identification of the precise nature and attributes of the time series of climatological data is very important and is usually the first step for water resources planning and management. Such exercise is very important for hydro-climatic extremes. In many instances, a climatic time series is generally not statistically independent but is comprised of patterns of persistence, cycles, trends or some other non-random components. To see the importance of the subject, this paper describes the statistical approach used to investigate the presence and extent of persistence, trend and periodicity in climatic time series. The methodology was applied to investigate the spatial distribution pattern of the indicative hydro-climatic variables over the Yamuna River basin of India. Hydro-climatic time series used in the analysis were annual rainfall; Monsoon and Non-monsoon rainfall; annual, Monsoon and Non-monsoon rainydays; onset of effective monsoon; and aridity index.

Keywords: Climate, time series, persistence, trend, periodicity, Yamuna river basin, India.

INTRODUCTION

Climate is the most important driving parameter that causes year-to-year variability in socio-economic and environmental systems including the availability of water resources. It affects the development and planning of water resources schemes such as flood prevention and control, drought management, food and fiber production, etc. Further, any change in climate will increase the uncertainty in water resources planning. Apart from this, changes in climatic pattern will have profound effects and consequences for natural and agricultural ecosystems and for society as whole. These changes could even alter the location of the major crop production regions on the earth [1]. The shifting from 'normal weather', with its associated extreme events will surely change the zones of crop adaptation and cultural practices required for successful crop production. Climate and weather induced instability in food and fibre supplies will alter social and economic stability and regional competitiveness [1]. Therefore, the analysis of hydro-climatic variables such as rainfall, potential evapotranspiration, etc becomes a prerequisite task to understand the climatic changes.

In recent years, there has been a considerable concern about the possibility of climatic changes. Alteration in our climate is governed by a complex system of atmospheric and oceanic processes and their interactions. Atmospheric processes also result in increase in surface-level ultraviolet radiation and changes in temperature and rainfall pattern. Human activities on the other hand are responsible for changes in ecosystem due to increased emissions rate of CO_2 and other green house gases. The evidence using state-of-art computer models incorporating as much of the theoretical understanding of the earth's weather suggests that global warming is occurring along with shifting patterns of rainfall and incidents of extreme weather events [2]. It was demonstrated that global surface warming has been taking place at the rate of 0.74 ± 0.18 °C over the period of 1906-2005 [2] and it was expected more in the next century than what has occurred during the past 10,000 years [3]. The increased atmospheric moisture content associated with warming might be expected to increase the global mean precipitation. Global annual land mean precipitation showed a small, but uncertain, upward trend of approximately 1.1 mm per decade (uncertainty ±1.5 mm) over 1901-2005. During the 20th century, precipitation has generally increased from latitudes 30° to 85°N over land; but notable decreases have occurred between latitudes 10 °S and 30°N in the last 30-40 years. In western Africa and southern Asia the linear trends in rainfall decrease during 1900-2005 were 7.5% per century (significant statistically at <1% level), whereas over much of northwest India shows increase in the rainfall with more than 20% per century [2]. At lower latitudes, especially seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (1-2 °C), which would increase the food risk [3]. Based on the data for the period of 1901-2005, it was demonstrated that all-India mean annual temperature had been rising at 0.05 °C/decade, with maximum temperature at +0.07 °C/decade and minimum temperature at +0.02 °C/decade [4]. As a result, the diurnal temperature range shows an increase of 0.05 °C/decade. However, in northern India, the average temperature is falling at the rate of -0.38 °C unlikely to rise in all-India average temperature (i.e at + 0.42 °C/Century) [5].

Change in the precipitation pattern is also reported for the 21st century. Kripalani *et al.* [6] reported an increasing trend

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in South-Asian mean monsoon precipitation associated with intensification of land–ocean pressure gradient during the establishment phase of the monsoon. At a regional scale, diversified precipitation pattern were investigated by various scientists / agencies. A declining trend in precipitation was observed over Greece [7], Canadian Prairies [8], Bologna in Italy [9]; whereas North Carolina [10], Mainland Spain [11] experienced rising trend. There was no trend identified in precipitation over the Iberian Peninsula [12] and Japan [13]. Beside these, a comprehensive review of precipitation changes was also carried out at global and regional level, and a decreasing precipitation trends was identified in Russia, Kazakhstan, China and Thailand with global increase in variance [14]. Probable causes of change in rainfall may be due to: (a) global climate shift [15] or weakening global monsoon circulation [16-18]; (b) reduction in forest cover [19-28] and change in land use including introduction of irrigated agriculture [29-32]; and (c) increasing aerosol due to anthropogenic activities [33-36].

In India, a diversified climate with large variations in the rainfall is experienced. Rainfall variability of the Indian monsoons has been extensively studied by several investigators [37-39]. An extensive review of studies of rainfall pattern of India excluding the Himalayan region was well presented by Basistha *et al.* [40]. Based on these studies, a consensus regarding evidence of insignificant trend in annual rainfall series can be reported, though divergences do exist depicting an increasing [41] or decreasing trend [42]. Regional analyses of the data revealed increasing rainfall trends over the Indus, Ganga, Brahmaputra, Krishna and Cauvery basins [42], the west coast [43], north Andhra Pradesh and northwest India [44], Rohtak and Kurukshetra of Haryana [45], Delhi [46], west Madhya Pradesh [47], coastal Orissa [48] and peripheries of the Rajasthan desert [49], but decreasing trends in the central Indian basins of Sabarmati, Mahi, Narmada, Tapi, Godavari and Mahanadi [42], east Madhya Pradesh and adjoining areas, northeast India [50] and parts of Gujarat [44], south Kerala [51,52] and central north Indian divisions [53]. Singh *et al.* [54] have indicated increasing trend of annual rainfall and relative humidity in north Indian River basins, though the least variation was observed in monsoon rainfall. Studies by Kothyari and Singh [55] and Kothyari *et al.* [21] reported decreasing rainfall trend over the Ganga basin, beginning around the second half of the 1960s. This was elaborated by Singh and Sontakke [56] to be increasing over western Indo-Gangetic Plains and decreasing (statistically insignificant, though) over the central part. IINC [57] depicts a decreasing summer monsoon rainfall trend over the state of Uttarakhand. Basistha *et al.* [40] attempted to explore changes in rainfall pattern in the Indian Himalayas during the 20th century and revealed that the most probable year of change in annual as well as monsoon rainfall in the region was 1964. There was an increasing trend up to 1964 (corroborating with all India and nearby plains), followed by a decreasing trend in 1965–1980 (exclusive to this region). In the entire region, changes are most conspicuous over the Shivaliks and the southern part of the Lesser Himalayas. Chase *et al.* [58] indicated a consistent reduction in intensity of all tropical monsoon systems since 1950. A decrease in monsoon precipitation in the central Himalayas (Tibet, China) was identified from early 1920s to the present [17]. However, a substantial global climate shift has been reported in the late 1960s affecting South America–Africa [59]. Apart from the rainfall pattern, other meteorological parameters show significant variations. Jhajharia *et al.* [60] analyzed the temporal characteristics of pan evaporation (Epan) under the humid conditions for northeast India and reported general decreasing trends in pre- and monsoon seasons. A declining trend in sunshine hours and wind speed, and increasing trend in relative humidity was also reported for most of the stations. Bandyopadhyay *et al.* [61] reported similar results for India in case of reference evapotranspiration (ETo) for the period of 1971-2002, which was mainly caused by a significant increase in relative humidity and a consistent significant decrease in the wind speed throughout the country. However, a general increase in rainfall was not found in recent years.

Looking into the aforesaid facts and studies, it can be stated that there is no consensus among the studies. Possibly, it may be due to analysis of climatic variable at regional scale, which induces loss of spatial information of the variable. Therefore, for water resources planning, it seems to be logical and compulsory to analyze the hydro-climatic variables at small scale that it can be rationalized at river basin scale. Though, the change in climate is governed by the complex system of atmosphere and oceanic processes and their interaction, but due to limitation on availability of wide variety of atmospheric data, this study focus on the analysis of indicative hydro-climatic parameters to demonstrate the climate change or changes in weather patterns.

In the present study, the Yamuna River basin was investigated to demonstrate the climatic fluctuation/variability which exhibit high spatio-temporal variability in terms of climate (semi-arid to humid subtropical climates) and topography. Parameters that directly influence the water resources and agricultural planning (viz., annual, monsoon and non-monsoon rainfall; number of annual, monsoon and non-monsoon rainydays; onset of effective monsoon; and aridity index) were considered.

STATISTICAL TEST FOR CLIMATOLOGICAL DATA

To define the climatic fluctuations exhibited in the hydro-climatic time series is an important aspect of the analysis. From a statistical point of view, the study of climatic fluctuations is a problem of time series analysis. Statistical evidence of persistence in such time series is equated with evidence of bona fide climatic fluctuations and said to be dependent. In many instances, a time series is generally not statistically independent but is comprised of persistence, cycles, trends or other non-random components. A steady and regular movement in a time series through which the values are on average either increasing or decreasing is termed a trend. This type of behavior can be local, in which case the nature of the trend is subject to change over short intervals of time, or, on the other hand, it can be visualize a global trend that is long lasting. If a trend in a hydrologic time series appear it is, in effect, part of a low frequency oscillatory movement induced by climatic factors or through change in land use and catchment characteristics. Looking into the importance of the deterministic components of climatic series, in the present study, the statistical test for persistence, trend and periodicity was discussed, and analyzed for the hydro-climatic variables of Yamuna River basin.

Persistence

For climatic variability and changes, definition of persistence given by WMO [62] is very common. According to this definition, persistence is a 'tendency for successive values of the series to "remember" their antecedent values, and to be influenced by them.' The value of r_1 has been used to detect the possible persistence in the observed year-to-year variations of normalized anomaly series and to examine its nature and magnitude. The approach proposed by WMO [62] and Matalas [63] was widely used later in many studies related to long-term climatic variations [64-72]. To test the persistence in the climatological time series normalized anomaly of the time series is used, which is obtained as follows:

$$X_t = (x_t - \bar{x}) / \sigma \tag{1}$$

where, X_t is the normalized anomaly of the series, x_t is the observed time series, $\bar{x}$ and σ are the long-term mean and standard deviation of annual/seasonal time series. All serial correlation coefficients of normalized climatic series are computed for lags $L = 0$ to m, where m is the maximum lag (i.e. $m = n/3$); n is the length of the series. The serial correlation coefficient was computed from eq. (2).

$$r_L = \frac{\sum_{t=1}^{n-L}(X_t - \bar{X}_t)\cdot(X_{t+L} - \bar{X}_{t+L})}{\left[\sum_{t=1}^{n-L}(X_t - \bar{X}_t)^2 \cdot \sum_{t=1}^{n-L}(X_{t+L} - \bar{X}_{t+L})^2\right]^{1/2}} \tag{2}$$

where, r_L is the lag-L serial correlation coefficient of the series. To test the significance of serial correlation, eq. (3) is used [73].

$$(r_L)_{t_g} = \frac{-1 \pm t_g\,(n - L - 1)^{1/2}}{n - L} \tag{3}$$

where, $(r_L)_{t_g}$ is the normally distributed value of r_L, t_g is the normally distributed statistic at g level of significance. The value of t_g are 1.645, 1.965 and 2.326 at significance level of 0.10, 0.05 and 0.01, respectively.

The hypothesis test was carried out at 0.05 level as this level is sufficient for engineering point of view. The 'null' hypothesis of the randomness of climatic series against the serial correlation is rejected for the large value of r_1. If r_1 of the series is not statistically significant or is significant but has a negative sign, it is assumed that the series does not contain the persistence and the appropriate null continuum is termed as 'white noise'. On the other hand, the persistence in the time series is characterized by a positive serial correlation. In this case, a "Markov red noise" type 'null' continuum is ensured using the r_2 and r_3 [62]. In addition to this significant negative r_1 are very likely to be indicative of high-frequency oscillations, whereas significant positive r_1 is likely to be indicative of low-frequency fluctuations and persistence in climatic series. Therefore, in the study serial correlation coefficients up to lag-3 were assessed.

Trend

There are several approaches for detecting the trend in the time series. These approaches can be either parametric or non-parametric. Parametric methods assumed the data should normally distributed and free from outliers. On the other hand, non-parametric methods are free from such assumptions. The most popularly used non-parametric tests for detecting trend in the time series is the Mann-Kendall (MK) test [74,75]. It is widely used for different climatic variables [76-78,8,79-87,40].

For original Mann-Kendall test, the time series must be serially independent in nature. However, in many real situations, the observed data are serially dependent (i.e., autocorrelated). The autocorrelation in the observed data will results in misinterpretation of trend test results. Cox and Stuart [88] stated that "positive serial correlation among the observations would increase the chance of significant answer, even in the absence of a trend". A closely related problem that has been studied is the case where seasonality exists in the data [76]. By dividing the observations into separate classes according to the season and then performing the Mann-Kendall trend test on the sum of the statistics from each season, the effect of seasonality can be eliminated. This modification is called the seasonal Mann-Kendall test [76,77]. Although the seasonal test eliminates the effect of seasonal dependence, it does not account for the correlation in the series within the season [77]. The same problem exists when yearly time series is considered for the analysis as it significantly autocorrelated. Therefore, in this paper, the original Mann-Kendall test is described along with its modified versions that accounts for the serially dependence in the data.

Mann-Kendall Test [74,75]

The Mann-Kendal (MK) test searches for a trend in a time series without specifying whether the trend is linear or nonlinear [89]. The Mann-Kendall test for detecting monotonic trends in hydrologic time series is described by Yue *et al.* [82]. It is based on the test statistics S, which is defined as:

$$S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{4}$$

where, x_j are the sequential data values, n is the length of the data set and

$$\operatorname{sgn}(t) = \begin{cases} 1, & for\ t > 0 \\ 0, & for\ t = 0 \\ -1, & for\ t < 0 \end{cases} \tag{5}$$

The value of S indicates the direction of trend. A negative (positive) value indicate falling (rising) trend. Mann-Kendall have documented that when $n \geq 8$, the test statistics S is approximately normally distributed with mean and variance as follows:

$$E(S) = 0 \tag{6}$$

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)\right] \tag{7}$$

where, m is the number of tied groups and t_i is the size of the i^{th} tie group. The standardized test statistics Z is computed as follows.

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}}, & for\ S>0 \\ 0, & for\ S=0 \\ \dfrac{S+1}{\sqrt{Var(S)}}, & for\ S<0 \end{cases} \quad (8)$$

The standardized Mann-Kendall statistics Z follows the standard normal distribution with zero mean and unit variance. If $|Z| \geq Z_{1-(\alpha/2)}$, the null hypothesis about no trend is rejected at the significance level α (10% in this study).

Modified Mann-Kendall Test

For Modified Mann-Kendall's test, the statistics *S* tends to normality for large *n*, with mean and variance given by:

$$E(S) = 0 \quad (9)$$

$$Var(S) = n(n-1)(2n+5)/18 \quad (10)$$

The statistics *S* is given by eq. (8):

$$S = a_{ij} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \quad (11)$$

With the same mean and variance as in eqs. (9) and (10), a modified version of the Mann-Kendall test which is robust in the presence of autocorrelation is proposed based on the modified variance of *S* given by eq. (12).

$$V^*(S) = Var(S) \cdot \frac{n}{n_s^*} = \frac{n(n-1)(2n+5)}{18} \cdot \frac{n}{n_s^*} \quad (12)$$

where, n/n_s^* represents a correlation due to the autocorrelation in the data. The n/n_s^* is evaluated using eq. (13).

$$\frac{n}{n_s^*} = 1 + \frac{2}{n(n-1)(n-2)} \times \sum_{i=1}^{n-1} (n-i)(n-i-1)(n-i-2)\rho_s(i) \quad (13)$$

In eq. (13), n is the actual number of the observations and $\rho_s(i)$ is the autocorrelation function of the ranks of the observations. The advantage of using eq. (12) and (13) for the evaluation of variance of S is that there is no need of either normalized data or their autocorrelation function. The autocorrelation of ranks of observations $\rho_s(i)$ is related with the parent autocorrelation function and is given as follows [75]:

$$\rho(i) = 2\sin\left(\frac{\pi}{6}\rho_s(i)\right) \quad (14)$$

Inverse of eq. (14) can therefore be used to evaluate the autocorrelation of rank $\rho_s(i)$ that appeared in eq. (13) and is given by eq. (15).

$$\rho_s(i) = \frac{6}{\pi}\sin^{-1}\left(\frac{\rho(i)}{2}\right) \quad (15)$$

The significance of the trends is tested by comparing the standardized test statistics Z.

$$Z = \frac{S}{[V^*(S)]^{0.5}} \quad (16)$$

A significant level of $\alpha = 0.1$ for the autocorrelation of the ranks $\rho_s(i)$ was used, which produce the best overall empirical significance level. The serial correlation of the ranks of the series and their significance test can be computed from eqs. (2) and (3).

Mann-Kendall Test with Pre-Whitening

An alternate approach to perform the trend analysis of time series with presence of serial correlation using the Mann-Kendall test is to remove the serial correlation from data first and then apply the test. Several approaches have been suggested for removing the serial correlation from a data set prior to applying the test. The pre-whitening approach is most common which involves computation of serial correlation and removing the correlation if the calculated serial correlation is significant at 0.05 significance level [81]. The pre-whitening is accomplished as follows:

$$X_t' = x_{t+1} - r_1 \times x_t \quad (17)$$

where, x_t = original time series with autocorrelation for time interval *t*; X_t' = pre-whitened time series; and r_1 = the lag-1 autocorrelation coefficient. This pre-whitened series is then subjected to Mann-Kendall test (i.e. eqs. 4 to 8) for detecting the trend.

Periodicity

Periodicity is one of the deterministic components in the time-series. Most of the climatic, atmospheric and hydrological time-series would consist of a combination of stochastic and deterministic components. The power spectrum is a method of analysis that was developed to handle the problem of periodicity in variations of natural events observed in time, such as in climatological and hydrological time series. Power spectrum analysis, also called generalized harmonic analysis, was derived from the principles first developed by Wiener [90, 91]. It is based on the premise that the time series are not necessarily composed of a finite number of oscillations, each with a discrete wavelength, but rather that they consist of virtually infinite number of small oscillations spanning a continuous distribution of wavelengths. The spectrum therefore, gives the distribution of variations in a time series over a continuous domain of all possible wavelengths.

Procedures for computing the power spectra may vary. Here, in this study, an approach described in WMO [62], developed by Tukey [92] and Blackman and Tukey [93] was employed. A detailed description of this approach can also be found in various textbooks [93-95]. It can be summarized through the following steps:

(i) First, all serial correlation coefficients of normalized climatic series (eq. 1) are computed for lags from $L = 0$ to m, where m is the maximum lag ($m = n/3$). The serial correlation coefficient can be computed using eq. (2).

(ii) Using the values of r_L, the 'raw' spectral estimates, $\hat{s}_k$ are computed using the following set of equations:

$$\hat{s}_0 = \frac{1}{2m}(r_0 + r_m) + \frac{1}{m}\sum_{L=1}^{m-1} r_L \tag{18}$$

$$\hat{s}_k = \frac{r_0}{m} + \frac{2}{m}\sum_{L=1}^{m-1} r_L \, Cos(\frac{\pi k L}{m}) + \frac{1}{m} r_m (-1)^k ;$$

for $k = 1, 2, ..., m-1$ (19)

$$\hat{s}_m = \frac{1}{2m}[r_0 + (-1)^m r_m] + \frac{1}{m}\sum_{L=1}^{m-1} (-1)^L r_L \tag{20}$$

Smallest is the value of k longest will be the wavelength of the spectrum, i.e. shortest wavelength is achieved at $k = m$.

(iii) The raw spectrum $\hat{s}_k$ is then smoothened with a 3-term weighted average. For smoothing, procedure suggested by Hanning was used [62].

$$s_0 = (\hat{s}_0 + \hat{s}_1)/2 \tag{21}$$

$$s_k = (\hat{s}_{k-1} + 2\hat{s}_k + \hat{s}_{k+1})/4 \text{; for } k = 1, 2, ..., m-1 \tag{22}$$

$$s_m = (\hat{s}_{m-1} + \hat{s}_m)/4 \tag{23}$$

The averaging procedure is performed to derive a constant estimate of the final spectrum in terms of $m+1$ discrete estimates [62].

Statistical Significance Test

The procedure for evaluating the results of power spectrum analysis mention in WMO [62] is described below:

(i) A 'null' hypothesis continuum is fitted to the computed spectrum. To start with, significance of the lag-1 serial correlation coefficient r_1 of the climatic series is tested at 90 percent confidence level. The 'null' hypothesis of the randomness of climatic series against the serial correlation is rejected for the large value of $(r_1)_t$. If r_1 is not significantly differ from zero, then series is regarded to be free from persistence. In this case, the appropriate null continuum is 'white noise'. In other words, a horizontal straight line, the value of which is everywhere equal to the average of the values of all the $m+1$ 'raw' spectral estimates (i.e., $\bar{s}$) in the computed spectrum (i.e., $S_k = \bar{s}$), is taken as the most suitable theoretical approach.

(ii) If the computed r_1 is positive and statistically significant, serial correlation coefficients for lag-2 and lag-3 are checked to see whether they approximate the exponential relations $r_2 \cong r_1^2$ and $r_3 \cong r_1^3$ [62]. If these relations are ensured with the computed serial coefficients, the approximate 'null' continuum is assumed as the simple "Markov red noise", whose shape depends on unknown value of the lag-1 serial correlation coefficient for a population ρ. Then the 'null' continuum can be created by following approximate procedure. By assuming that the sample r_1 is an unbiased estimation of ρ, various chose of the Harmonic number of k between $k = 0$ to m are assessed:

$$S_k = \bar{s}\left(\frac{1 - r_1^2}{1 + r_1^2 - 2r_1 \, Cos(\frac{\pi k}{m})}\right) \tag{24}$$

where, $\bar{s}$ is the average of all $m+1$ 'raw' spectral estimates $\hat{s}_k$ in the computed spectrum. The resulting values of S_k can be plotted superposed on the sample spectrum, and a smoothed curve passed through these values to reach the required null continuum.

(iii) If r_1 is statistically significant but a few serial correlation coefficient for higher lags do not show the required exponential relations (i.e., $r_2 \cong r_1^2$ and $r_3 \cong r_1^3$) with r_1, then doubt arises as to whether the simple Markov-type persistence is the dominant form of non-randomness in series of climatic observations. Nevertheless, WMO [62] suggested that this procedure could be continued with just as before to compute the red noise continuum for r_1.

(iv) At this stage of the power spectrum analysis a first choice of the null continuum is made, and this selected continuum is superposed on the studied spectrum. In this case, it would be possible to make an assessment of the spectrum for its consistency with the chosen continuum. Then, the value of each spectral estimate s_k is compared with the local value of the null continuum.

The statistic associated with the each spectral estimate is the ratio of the magnitude of the spectral estimate to the local magnitude of the continuum (red noise continuum). Tukey [92] found that the quantity of this ratio is distributed as Chi-square divided by the degree of freedom. The degree of freedom, ν, of each estimate of a computed spectrum is given as follows.

$$\nu = (2n - m/2)/m \tag{25}$$

The ratio of any sample spectral estimate s_k to its local value of the red noise continuum is then compared with critical percentage-point levels of χ^2/ν distribution for the proper ν value. This comparison produces the required statistical significance level. The χ^2 value can be obtained from standard statistical books.

(v) In a sample spectrum, critical percentage-point levels of the χ^2/ν distribution, e.g. the 0.95 confidence level, is the same for all spectral estimates s_k. The confidence limits are finally derived by multiplying the 'null' continuum (i.e. S_k) with the χ^2/ν.

(vi) Finally, the cycle associated in the time series is computed as follows.

$$P = 2m / L \qquad (26)$$

APPLICATION

The test described for the persistence, trend and periodicity was applied on the hydro-climatic data of Yamuna River basin. The River Yamuna is the largest tributary of River Ganga (Fig. **1**). This river is as prominent and sacred as the great River Ganga itself. The total length of the Yamuna River from its origin at Saptrishi Kund to its confluence with Ganga at Allahabad is 1376 km traversing through five states. The main stream of the river originates from the Yamunotri glacier (Saptrishi Kund) near Bander punch peaks (38°59' N 78°27'E) in the Mussoorie range of the lower Himalayas at an elevation of about 6320 meter above mean sea level in Uttarkashi district of Uttarakhand. The head waters of the Yamuna river are formed by several melt streams, the chief of them gushing out of the morainic smooth at an altitude of 3250 m, 8 km North West of the Yamunotri hot springs at latitude 31°02'12" N and longitude 78°26'10". In the upper reaches, the Rishi Ganga (right bank), and Unta and Hanuman Ganga (left bank) join the Yamuna River. In the lower Himalayan ranges the Yamuna River receives water from Kamal, Tons, Giri and Bata on its right bank and on its left bank receives the Aglag and Asan river tributaries. The Chambal, Betwa, Sind and Ken are the important tributaries joining the Yamuna on the right bank in the plain, and the Hindon River on the left bank. Among all these tributaries, Tons at the hills and Chambal at the plains are the most important tributaries in terms of their discharges. The Tons is the principal source of water in the mountainous range and generally carries more water than the mainstream. In the plains, during the non-monsoon period, the River Chambal contributes about 5-10 times more water to the Yamuna than its own flow. However, since 2003, there is a significant reduction in the discharge of the Chambal River. In the basin, most of the rainfall occurs during the monsoon. The impact of this rainfall pattern mostly influences flooding. During the non-monsoon period the river flow is reduced significantly and some rivers stretches become dry. The Yamuna River carries almost 80% of the total annual flow during the monsoon period.

The Yamuna basin (Fig. **1**) is comprised of a total drainage area of 345848 km^2 extended between the latitudes of 22˚24'22.3" to 31˚30'56.6" and longitudes of 73˚17'37.26" to 81˚57'42.16". Based on the topography (i.e. elevation), the Yamuna basin can be divided into three regions, i.e. the hilly region with drainage area of 11700 km^2 (> 600 m above msl), the foot hills and Plateau region having drainage area of 172917 km^2 (300-600 m above msl), and plains and valleys with drainage area of 161231 km^2 (100-300 m above msl). The majority of the soil type is alluvial and covers about 42% of the basin area, whereas calcareous Seirozemic soils contribute a minimum with about 0.5% of the basin area. Landuse in the basin can be broadly classified as cultivable (60.0%), non-arable (27.5%) and forest land (12.5%). Out of a total cultivable land (i.e. 60%), actual cultivable land is only 51.9% and total habited land is approximately 2.9%. Forest land in the basin pertains mainly to upper Himalayan catchments (81.4%).

Data Processing

The climatic series subjected to the analysis are: (i) annual rainfall; (ii) monsoon and non-monsoon rainfall; (iii) annual rainydays; (iv) monsoon and non-monsoon rainydays; (v) onset of effective monsoon (OEM); and (vi) annual aridity index (AI). For rainfall data, one degree grid data of daily rainfall for the period 1951 to 2002 maintained by the India Meteorological Department (IMD) was used. Sixty five rain-grids points that fall under the Yamuna basin with 1° buffer were used in the analysis. The monsoon rainfall was derived from the daily data for the period July to October and rest of

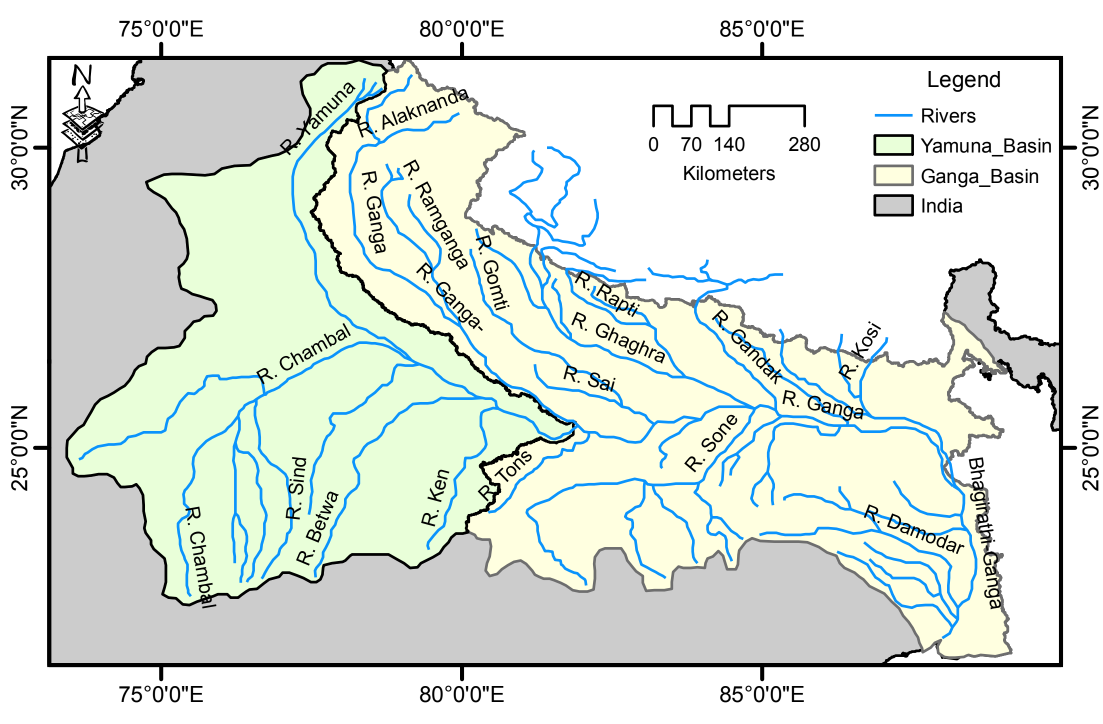

Fig. (1). Ganga basin including Yamuna river basin.

the period was considered as non-monsoon. The OEM, an important governing agro-climatic parameter for planning of *kharif* crops was estimated using the Ashokraj criteria [96], which uses the daily rainfall and potential evapotranspiration data. The potential evapotranspiration was estimated using the Thornthwaite method [97]. A seven days rainfall spell satisfying the following conditions are terms as OEM. These conditions are: (i) first day rainfall in the seven days spells should be more than evaporation of that particular day; (ii) a day with-more than 3 mm of rainfall is considered to be a rainy day; (iii) total rainfall during the seven days spell is more than (3× PET + 10) mm; and (iv) at least four out of seven days are rainy days.

The aridity index or AI was estimated following the procedure of United Nations Environment Programme [98] as:

$$AI = (R / PET) \times 100\ \% \tag{27}$$

where, *AI* is the aridity index (%), *R* is the annual rainfall (mm) and *PET* is the annual potential evapotranspiration (mm). *AI* values below 100 % shows annual moisture deficit in average climatic conditions.

The spatial distribution pattern of these hydro-climatic parameters (*viz*. annual mean, monsoon mean and non monsoon mean rainfall; annual mean, monsoon mean and non-monsoon mean rainydays; mean OEM; and mean aridity index) is shown in Fig. (**2**).

RESULTS AND DISCUSSIONS

Persistence

Persistence is evident in long time series of climatic observations characterized by a positive serial correlation. Significant negative r_1 are very likely to be indicative of high-frequency oscillations, whereas significant positive r_1 is likely to be indicative of low-frequency fluctuations and persistence in climatic series. This feature will be further elaborated in following section (i.e. 'periodicity'). In the study, serial correlation for all the lags (i.e. L = 0 to m) were computed for all the grid points. However, serial correlation coefficients up to lag 3 was assessed. Serial correlation coefficient up to lag-3 is plotted for all the climatic variables except non-monsoon, although all the variables were analyzed. These plots are shown in Figs. (**3** to **5**), which give the spatial distributions pattern of lag-1 to lag-3 serial correlation coefficients for the considered variables over the Yamuna river basin. A regularized spline method was used as an interpolation technique to produce the spatial distribution pattern of the variables.

It s evident from the Figs. (**3** to **5**) that most of the grid point data shows statistically insignificant serial correlation coefficient (SC) for all the hydro-climatic variables (i.e. annual, monsoon and non monsoon ranfall; annual, monsoon and non monsoon rainydays; OEM and aridity index). However, few grid data of annual and monsoon rainfall near the central and northern part of the basin shows the existence of persistence characterized by significant lag-1 SC; whereas, few grid data points in the south-east part of the basin shows high frequency variability as characterized by significant negative lag 1-SC (Fig. **3**). The spatial distribution of lag 1-SC of non monsoon (Fig. **4**) indicated the presence of persistence in the few grid data in the northern part of the basin. Lag-1 SC of annual rainfall and aridity index shows the similar distribution pattern, which might be due to the more dependence of aridity index on annual rainfall (Figs. **3** and **5**).

Based on Figs. (**3** to **5**), a little positive spatial coherence characterized by lag-1 SC was identified for annual and monsoon rainfall, annual rainydays and aridity index. Looking into the Figs. (**3** to **5**) and by comparing the spatial pattern of lag-2 SC with the lag-1 SC, it was indicated that coherent area of significant positive lag-2 SC are greater than that of the lag-1. The lag-2 SC coefficients are mostly positive but insignificant for all the variables except for the non-monsoon rainfall, non-monsoon rainydays and OEM. On the other hand, by analyzing the lag-3 SC of the hydro-climatic variables, it was evident that the percentage coherent area is significantly reduced for all the variables. However, it is increase in case of non-monsoon rainfall, non-monsoon rainydays and OEM. Apart from this, detailed table of the serial correlation coefficients up to lag-3 are also prepared for all the variables. But, serial correlation coefficients up to lag-3 are presented for monsoon rainfall, rainydays and OEM only (Tables **1** to **3**), though the summarized table (Table **4**) was prepared to visualize the overall temporal characteristics of the variables.

Trend Analysis

In the trend analysis, time series of the entire variable from 1951 to 2002 were subjected to three non-parametric statistical tests, viz. Mann-Kendall test, Modified Mann-Kendall test and Mann-Kendall test with pre-whitening of series. Two later tests are basically designed for the series having significant lag-1 SC. The comparative results were obtained from all the three tests for all the considered variables. However, the sample results of trend analysis for monsoon rainfall and OEM are presented (Tables **5** - **6**). These Tables (Table **5** - **6**) also include the value of lag-1 SC along with their lower and upper limits at 95% confidence level. Based on Tables **5** and 6, it is apparent that the times series with significant negative lag-1 SC do not have the significant trend.

The spatial pattern of lag-1 SC of the hydro-climatic variables is depicted in Figs. (**3** to **5**). The summarized statistics of trend analysis is given in Table **7**. Though, the trend results were produced using all the tests but spatial pattern of Z-statistics was presented using the results obtained from modified Mann-Kendall test. For pattern analysis, regularized spline method was used for interpolation of the data. The spatial pattern of the trend statistics for the hydro-climatic variables is shown in Fig. (**6**) (annual, monsoon, and non-monsoon rainfall; and annual, monsoon, and non-monsoon rainydays) and Fig. (**7**) (OEM and aridity index). The patterns ware classified based on the 90 % confidence level (i.e. $Z < -1.645$; $-1.645 < Z < 0.0$; $0.0 < Z < 1.645$; and $Z > 1.645$). These interval ($Z < -1.645$; $-1.645 < Z < 0.0$; $0.0 < Z < 1.645$; and $Z > 1.645$) shows the significant negative trend, insignificant negative trend, insignificant positive trend, and significant positive trend at 90% confidence interval, respectively.

Based on the analysis (Fig. **6** and Table **7**), it can be observed that annual rainfall and monsoon rainfall shows a overall declining trend though the scattered patches of the basin shows insignificant rising trend. The trend statistics for

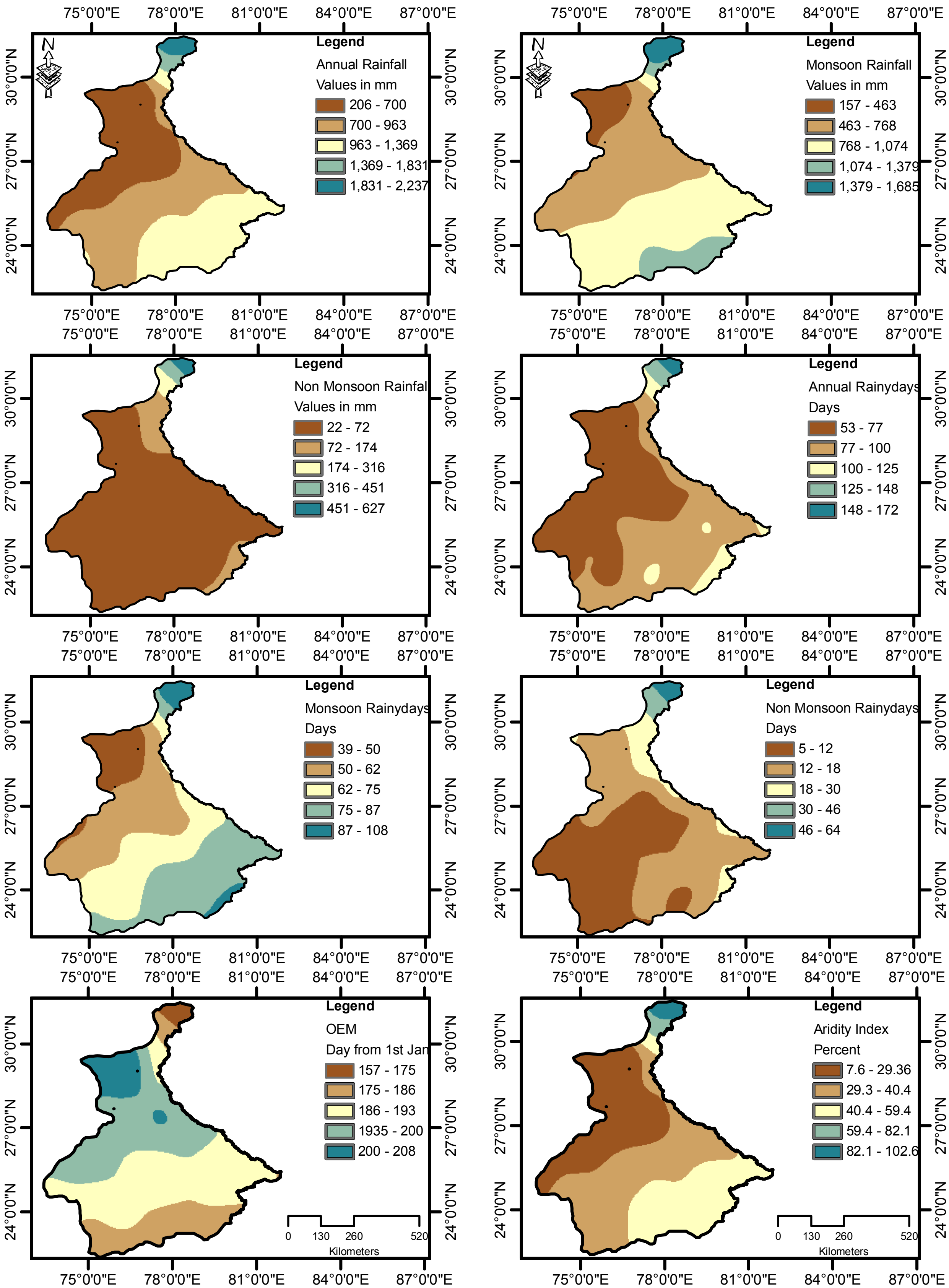

Fig. (2). Spatial distribution pattern of mean hydro-climatic parameters in Yamuna river basin.

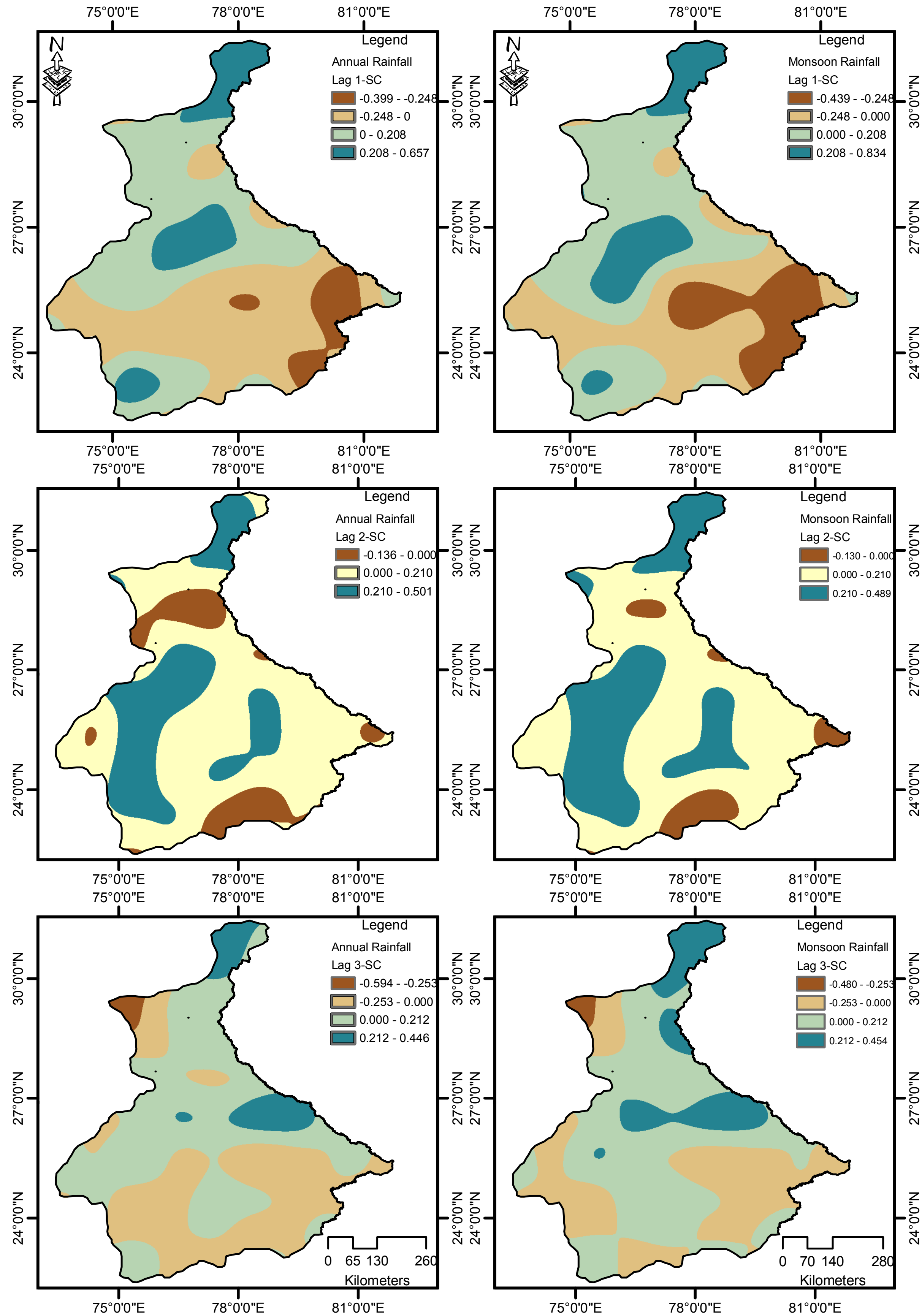

Fig. (3). Spatial distribution pattern of serial correlation of annual mean and monsoon mean rainfall up to lag 3.

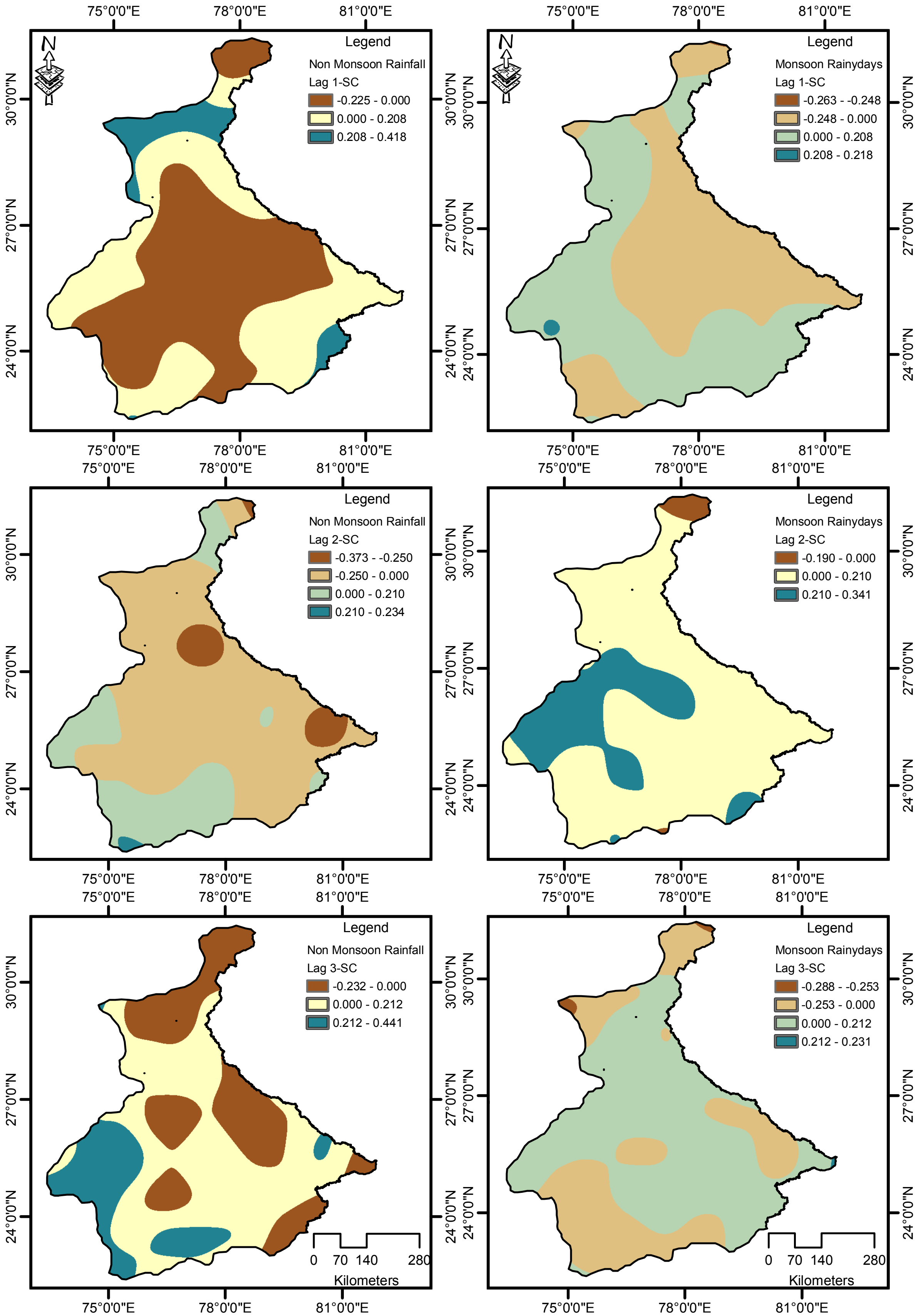

Fig. (4). Spatial distribution pattern of serial correlation of non-monsoon rainfall and monsoon rainydays up to lag 3.

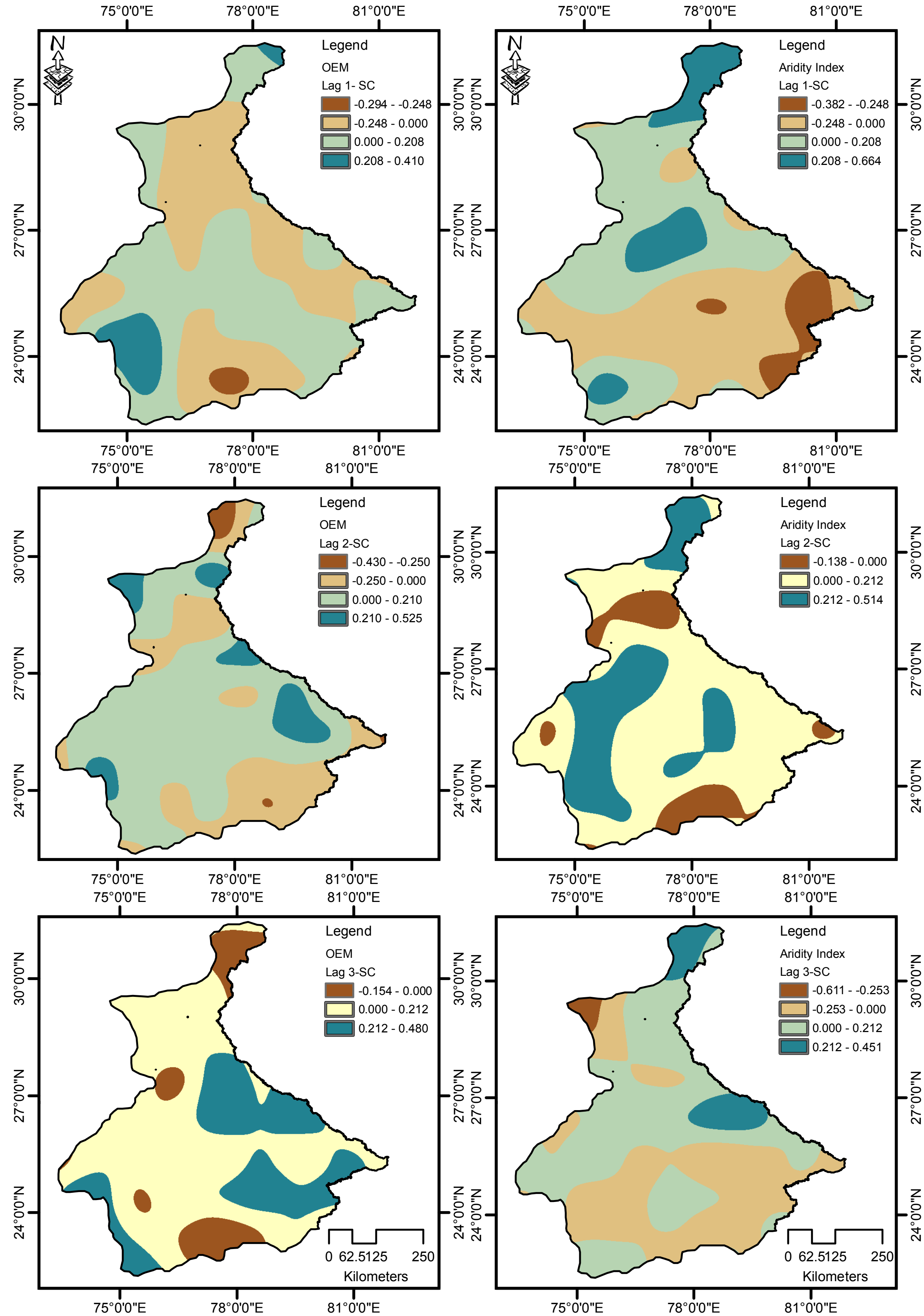

Fig. (5). Spatial distribution pattern of serial correlation of OEM and aridity index up to lag 3.

Table 1. Results of Serial Correlation (Lag 1 to 3) and Power Spectrum Analysis for Monsoon Rainfall

S.No.	r1	r2	r3	L	Cycles		Cont.	S.No.	r1	r2	r3	L	Cycles		Cont.
					90 %	95 %							90 %	95 %	
1	0.00	-0.18	-0.18	7	4.9		WN	31	-0.27	0.25	-0.10	13	2.6		WN
				8	4.3							14		2.4	
2	0.05	-0.01	0.04	2	17.0		WN					15		2.3	
3	0.05	0.02	0.08	2	17.0		WN					16	2.1		
4	-0.09	0.11	-0.05				WN	32	-0.25	0.10	-0.08	14		2.4	WN
5	-0.12	-0.07	-0.05				WN					15		2.3	
6	0.40	0.37	0.42	12	2.8		RN	33	-0.41	0.07	0.00	13		2.6	WN
7	-0.04	0.03	-0.12									14		2.4	
8	-0.04	-0.02	0.18	11	3.1		RN					15		2.3	
				12		2.8	WN	34	-0.02	-0.06	-0.06	7	4.9		WN
9	-0.05	0.13	0.02	2		17.0		35	-0.12	0.11	-0.04	15		2.3	WN
10	0.22	0.24	0.01	1	34.0			36	0.00	0.02	0.04				WN
				2		17.0	WN	37	0.20	0.18	-0.07	1		34.0	WN
				3	11.3							2		17.0	
11	0.15	0.23	0.01	2		17.0	WN	38	0.12	0.28	0.09	1	34.0		WN
				3		11.3						2	17.0		
12	-0.03	-0.03	0.04				WN	39	0.35	0.30	0.27	2	17.0		RN
13	-0.02	-0.11	-0.02				WN					12	2.8		
14	-0.34	0.07	0.01	14		2.4	WN	40	0.26	0.14	0.22	12		2.8	RN
				15		2.3						13		2.6	
15	-0.18	-0.02	0.12				WN	41	0.11	0.23	0.31	1	34.0		WN
16	-0.14	0.10	-0.01					42	0.02	0.12	0.27				WN
17	0.07	0.05	-0.01	2	17.0		WN	43	-0.14	0.06	0.06	13		2.6	
18	-0.20	0.15	-0.03	14	2.4		WN					14		2.4	
				15		2.3		44	-0.13	0.15	0.04	13	2.6		WN
19	-0.08	0.39	-0.11	2		17.0	WN					14		2.4	
				3		11.3						15	2.3		
				15	2.3			45	0.40	0.30	0.13	13	2.6		RN
				16		2.1		46	0.18	0.04	0.19	2		17.0	WN
				17	2.0							3	11.3		
20	-0.04	0.17	0.13	2		17.0	WN	47	0.11	0.24	0.10	2	17.0		WN
				3		11.3						3	11.3		
21	-0.22	0.23	0.13	2	17.0		WN	48	0.14	0.15	0.06	4	8.5		WN
				3	11.3							5	6.8		
				13	2.6			49	-0.10	-0.01	0.13	12	2.8		WN
				14		2.4		50	-0.07	0.06	0.09	13		2.6	WN

Table 1. contd….

S.No.	r1	r2	r3	L	Cycles		Cont.	S.No.	r1	r2	r3	L	Cycles		Cont.
					90 %	95 %							90 %	95 %	
22	-0.21	0.20	0.01	12	2.8		WN	51	0.06	0.04	-0.16	4	8.5		WN
				13	2.6							5		6.8	
				14	2.4			52	0.15	0.09	-0.17	4	8.5		WN
				15	2.3							5		6.8	
23	-0.22	0.20	-0.09	14	2.4		WN	53	0.07	-0.02	0.07	3	11.3		WN
				15		2.3						4	8.5		
24	-0.37	0.07	-0.03	13	2.6		WN	54	-0.03	0.04	0.26	13		2.6	WN
				14		2.4		55	0.21	0.34	0.23	1		34.0	WN
				15		2.3		56	0.17	0.22	0.11	2		17.0	WN
25	-0.21	0.09	-0.13	15		2.3	WN					3		11.3	
				16	2.1			57	0.13	0.22	0.20	13	2.6		WN
26	-0.15	0.20	0.13	2	17.0		WN	58	0.13	0.29	-0.01	14	2.4		WN
				12		2.8		59	-0.12	-0.11	0.06	13	2.6		WN
27	0.04	0.08	-0.04	2	17.0		WN					14	2.4		
				5	6.8			60	0.59	0.48	0.41	14	2.4		WN
28	0.20	0.43	0.21	1		34.0	WN	61	0.44	0.28	0.13	14	2.4		RN
				2		17.0		62	0.28	0.14	0.14	14	3.4		RN
29	0.23	0.20	0.06	2		17.0	WN	63	-0.25	-0.01	0.06	14		2.4	WN
				3		11.3						15	2.3		
30	-0.26	0.12	-0.01	14		2.4	WN	64	0.40	0.20	0.01	15		2.3	RN
				15		2.3		65	0.48	0.41	0.24	15	2.3		RN

r_1 = lag-1 SC, r_2 = lag-2 SC, r_3 = lag-3 SC, L = lag corresponding to significant spectral estimates, Cycles = periodicity (2m/L), Cont. = null continuum, WN = white noise, RN = Markov red noise

Table 2. Results of Serial Correlation (Lag 1 to 3) and Power Spectrum Analysis for Monsoon Rainydays

S.No.	r1	r2	r3	L	Conf. Level		Cont.	S.No.	r1	r2	r3	L	Conf. Level		Cont.
					90	95							90	95	
1	0.10	0.11	0.00	2	17.0	0.0	WN	35	-0.24	0.10	0.06	14	2.4	2.4	WN
2	-0.03	0.14	0.14				WN					15	2.3	2.3	
3	0.01	0.10	0.00				WN	36	0.11	0.12	0.00	2	17.0	17.0	WN
4	-0.04	0.20	-0.04				WN	37	0.15	0.28	0.15	1	34.0	34.0	WN
5	0.07	-0.12	-0.18	6	5.7	0.0	WN					2	17.0	17.0	
				7	4.9	0.0		38	0.08	0.24	0.05	2	17.0	17.0	WN
6	0.08	0.15	0.06	2	17.0	0.0	WN	39	-0.07	0.21	0.06	2	17.0	17.0	WN
7	0.32	0.12	-0.09				RN	40	-0.09	0.27	0.06	2	17.0	0.0	WN
8	0.10	0.26	0.19	1	34.0	34.0	WN					14	2.4	0.0	
				2	17.0	0.0						15	2.3	0.0	

Table 2. contd….

S.No.	r1	r2	r3	L	Conf. Level		Cont.	S.No.	r1	r2	r3	L	Conf. Level		Cont.
					90	95							90	95	
				13	2.6	0.0		41	-0.07	0.18	0.00	15	2.3	0.0	WN
9	-0.04	0.15	-0.01	12	2.8	0.0	WN	42	-0.03	0.11	-0.01	5	6.8	0.0	WN
10	-0.07	0.16	-0.13				WN					14	2.4	0.0	
11	0.06	0.15	-0.09	2	17.0	0.0	WN	43	-0.05	0.06	0.03	15	0.0	0.0	
12	0.04	0.18	0.01	2	17.0	17.0	WN	44	0.06	0.05	0.08	5	6.8	0.0	WN
13	0.02	0.03	-0.08	5	6.8	0.0	WN	45	0.13	0.12	0.18	1	34.0	34.0	WN
14	0.09	0.27	0.10	1	34.0	0.0	WN					2	17.0	17.0	
				2	17.0	17.0		46	0.19	0.17	0.13	1	34.0	34.0	WN
15	0.01	0.15	0.14	2	17.0	17.0	WN					2	17.0	17.0	
				14	2.4	0.0		47	0.02	0.21	0.09	2	17.0	17.0	WN
16	-0.01	0.01	0.08	12	2.8	2.8	WN					3	11.3	0.0	
17	0.04	0.09	0.02	2	17.0	0.0	WN	48	-0.08	0.12	0.11				WN
18	0.21	0.22	-0.03	1	34.0	0.0	WN	49	-0.13	0.09	0.06	14	2.4	2.4	WN
				2	17.0	17.0		50	-0.01	0.14	0.11	2	17.0	0.0	WN
				3	11.3	0.0						14	2.4	0.0	
19	0.07	0.07	-0.13	2	17.0	0.0	WN	51	0.14	0.07	-0.01	2	17.0	0.0	WN
20	0.03	0.28	0.08	2	17.0	17.0	WN					5	6.8	0.0	
21	-0.05	0.11	0.12	2	17.0	0.0	WN					14	2.4	0.0	
				14	2.4	0.0		52	0.11	0.05	-0.06	3	11.3	11.3	WN
22	0.13	0.14	0.12	2	17.0	17.0	WN					4	8.5	8.5	
23	0.01	0.04	0.06				WN	53	0.08	0.11	0.15				WN
24	0.14	0.12	0.07	5	6.8	0.0	WN	54	-0.11	0.20	-0.01				WN
25	0.01	0.11	0.18	14	2.4	0.0	WN	55	0.10	0.11	0.16				WN
26	0.09	0.20	0.09	1	34.0	34.0	WN	56	-0.01	0.19	-0.02	2	17.0	0.0	WN
27	0.16	0.28	0.06	1	34.0	34.0	WN					3	11.3	0.0	
				2	17.0	17.0		57	0.04	0.16	0.06	2	17.0	0.0	WN
28	0.07	0.32	0.02	1	34.0	34.0	WN	58	0.37	0.28	0.08				RN
				2	17.0	17.0		59	0.05	0.16	0.09	1	34.0	0.0	WN
29	-0.05	0.11	-0.01	14	2.4	0.0	WN	60	0.01	0.08	-0.06				WN
30	-0.06	0.17	0.00	14	2.4	2.4	WN	61	0.08	0.07	-0.10	5	6.8	0.0	WN
31	-0.08	0.20	0.10	14	2.4	0.0	WN	62	0.05	-0.02	-0.01				WN
32	-0.03	0.11	0.05				WN	63	-0.18	0.27	-0.09	15	2.3	0.0	WN
33	-0.05	0.05	-0.06				WN					16	2.1	0.0	
34	-0.01	0.12	0.15	14	2.4	0.0	WN	64	0.28	0.10	0.03				RN
								65	0.43	0.36	0.27	14	2.4	0.0	RN

r_1 = lag-1 SC, r_2 = lag-2 SC, r_3 = lag-3 SC, L = lag corresponding to significant spectral estimates, Cycles = periodicity (2m/L), Cont. = null continuum, WN = white noise, RN = Markov red noise

Table 3. Results of Serial Correlation (Lag 1 to 3) and Power Spectrum Analysis for OEM

S.No.	r1	r2	r3	L	Conf. Level		Cont.	S.No.	r1	r2	r3	L	Conf. Level		Cont.
					90	95							90	95	
1	0.10	0.06	0.08	4	8.5	0.0	WN	36	0.04	-0.16	0.09				WN
2	0.08	-0.07	0.38	10	3.4	3.4	WN	37	0.17	0.08	0.16	1	34.0	0.0	WN
3	0.05	-0.03	0.42	1	34.0	0.0	WN					2	17.0	0.0	
				2	17.0	0.0		38	0.16	0.11	0.08	2	17.0	0.0	WN
				12	2.8	0.0		39	-0.04	0.14	0.10	14	2.4	0.0	WN
				13	2.6	2.6		40	0.14	0.02	0.33	1	34.0	0.0	WN
4	0.03	0.06	0.12				WN					9	3.8	0.0	
5	0.00	-0.18	-0.03	7	4.9	4.9	WN	41	-0.19	-0.02	0.22	13	2.6	0.0	WN
				8	4.3	4.3						14	2.4	0.0	
6	0.17	0.07	0.06	1	34.0	0.0	WN	42	0.09	0.29	0.29	1	34.0	0.0	WN
7	0.23	-0.04	-0.03	6	5.7	0.0	WN					13	2.6	0.0	
				9	3.8	0.0		43	-0.07	-0.13	0.17	9	3.8	3.8	WN
8	0.12	-0.09	-0.06				WN					13	0.0	0.0	
9	0.04	0.13	0.34	1	34.0	34.0	WN	44	-0.19	-0.14	-0.02	14	2.4	2.4	WN
10	0.32	0.13	0.12	7	4.9	0.0	RN	45	-0.01	-0.01	0.19				WN
11	-0.14	-0.05	0.01				WN	46	0.03	-0.08	0.10				WN
12	-0.29	0.06	-0.12	15	2.3	0.0	WN	47	-0.07	0.00	-0.04	8	4.3	4.3	WN
				16	2.1	2.1						9	3.8	0.0	
				17	2.0	2.0		48	0.00	0.19	0.32	1	34.0	0.0	WN
13	-0.10	-0.21	-0.02	9	3.8	0.0	WN					13	2.6	0.0	
				10	3.4	3.4		49	-0.03	0.29	0.19	13	2.6	0.0	WN
14	0.01	-0.19	0.17	8	4.3	0.0	WN	50	0.03	-0.10	0.22	9	3.8	3.8	WN
				9	3.8	3.8						10	3.4	0.0	
				10	3.4	0.0		51	-0.14	-0.11	0.09	9	3.8	0.0	WN
15	0.04	0.03	0.06				WN					13	2.6	0.0	
16	0.07	-0.02	-0.11				WN	52	0.05	0.19	0.17	1	34.0	34.0	WN
17	-0.10	-0.15	0.21	10	3.4	0.0	WN					2	17.0	0.0	
				11	3.1	3.1		53	-0.10	-0.02	0.20	11	3.1	0.0	WN
				12	2.8	0.0		54	-0.15	-0.19	0.13	6	5.7	0.0	WN
18	0.31	0.29	0.30				RN					11	3.1	3.1	
19	0.32	0.04	-0.01	8	4.3	4.3						12	2.8	2.8	
20	-0.04	0.04	0.14	11	3.1	0.0	WN					13	2.6	0.0	
21	0.02	0.04	0.21				WN	55	0.19	0.30	0.07	1	34.0	34.0	WN
22	0.05	-0.10	0.35	9	3.8	3.8	WN	56	-0.05	0.06	0.08				WN
23	0.14	-0.06	0.24	9	3.8	0.0	WN	57	-0.07	0.33	0.07	2	17.0	0.0	WN
24	0.00	-0.13	0.24				WN					15	2.3	2.3	

Table 3. contd….

S.No.	r1	r2	r3	L	Conf. Level		Cont.	S.No.	r1	r2	r3	L	Conf. Level		Cont.
					90	95							90	95	
25	0.17	-0.15	0.18	8	4.3	4.3	WN	58	0.02	0.03	-0.25	4	8.5	8.5	WN
				9	3.8	3.8						5	6.8	6.8	
26	-0.16	-0.05	-0.08	10	3.4	0.0	WN	59	0.01	0.13	0.08	13	2.6	0.0	WN
27	-0.11	0.03	0.15	13	2.6	2.6	WN	60	0.05	-0.28	-0.04	8	4.3	4.3	WN
28	0.12	0.10	0.15				WN					9	3.8	3.8	
29	0.03	0.12	0.14	14	2.4	2.4	WN	61	0.12	0.12	-0.13	2	17.0	0.0	WN
30	0.03	0.09	0.10	14	2.4	0.0	WN	62	0.16	-0.03	0.02				WN
31	0.10	0.13	0.22				WN	63	0.12	-0.19	-0.08	5	6.8	0.0	
32	-0.10	0.26	0.14	13	2.6	2.6	WN					6	5.7	5.7	WN
33	0.01	0.20	0.21	12	2.8	0.0	WN	64	-0.06	-0.19	0.08	8	4.3	0.0	WN
				13	2.6	2.6						9	3.8	3.8	
34	0.02	-0.21	0.17	8	4.3	0.0	WN	65	-0.04	-0.14	0.13	9	3.8	0.0	WN
				9	3.8	0.0									
35	-0.12	-0.25	0.20	9	3.8	3.8	WN								
				10	3.4	3.4									

r_1 = lag-1 SC, r_2 = lag-2 SC, r_3 = lag-3 SC, L = lag corresponding to significant spectral estimates, Cycles = periodicity (2m/L), Cont. = null continuum, WN = white noise, RN = Markov red noise

Table 4. Summarized Result of Persistence Analysis

S. No.	Variable	No. Series Sowing Significant Positive			No. (%) Series Sowing Persistence	No. (%) Series Sowing Significant Negative		
		r_1	r_2	r_3		r_1	r_2	r_3
1	Annual Rainfall	13 (20.00)	16 (24.60)	5 (7.69)	13 (20.00)	3 (4.61)	0 (0.00)	0 (0.00)
2	Monsoon Rainfall	12 (18.46)	19 (29.23)	9 (13.84)	12 (18.46)	6 (9.23)	0 (0.00)	0 (0.00)
3	Non-Monsoon Rainfall	13 (20.00)	2 (3.07)	14 (21.50)	13 (20.00)	0 (0.00)	3 (4.61)	1 (1.54)
4	Annual Rainydays	17 (26.15)	12 (18.46)	2 (3.07)	17 (26.15)	0 (0.00)	0 (0.00)	2 (3.07)
5	Monsoon Rainy-days	5 (7.69)	14 (21.54)	1 (1.54)	5 (7.69)	0 (0.00)	0 (0.00)	0 (0.00)
6	Non-Monsoon Rainydays	22 (33.84)	2 (3.07)	10 (15.38)	22 (33.84)	0 (0.00)	2 (3.07)	2 (3.07)
7	OEM	4 (6.15)	6 (9.23)	14 (21.5)	4 (6.15)	1 (1.54)	1 (1.54)	0 (0.00)
8	Aridity Index	13 (20.00)	16 (24.60)	4 (6.15)	13 (20.00)	3 (4.61)	0 (0.00)	0 (0.00)

Values in the parenthesis are the percentage of total time series

Table 5. Lag-1 Serial Correlation and Mann-Kendall's Z-Statistics of Monsoon Rainfall of the Yamuna River Basin [$r_1(l)$ = -0.248 and $r_1(u)$ = 0.208]

Grid Location		r_1	Z-MK			Grid Location		r_1	Z-MK		
Lat	Long		Org	Mod	PW	Lat	Long		Org	Mod	PW
21.5N	75.5E	0.003	0.3	0.3	0.3	25.5N	81.5E	-0.022	-0.387	-0.387	-0.387
22.5N	74.5E	0.052	-0.655	-0.655	-0.655	25.5N	82.5E	-0.123	1.065	1.065	1.065
22.5N	75.5E	0.047	-0.513	-0.513	-0.513	26.5N	73.5E	-0.004	0.292	0.292	0.292
22.5N	76.5E	-0.09	-0.923	-0.923	-0.923	26.5N	74.5E	0.204	-0.181	-0.181	-0.181
22.5N	77.5E	-0.121	-0.702	-0.702	-0.702	26.5N	75.5E	0.119	-1.405	-1.405	-1.405
22.5N	78.5E	**0.396**	**-4.34**	0.021	**-3.338**	26.5N	76.5E	**0.346**	-1.981	0.005	**-2.359**
22.5N	79.5E	-0.039	0.016	0.016	0.016	26.5N	77.5E	**0.257**	**-2.044**	**-2.044**	**-2.438**
23.5N	73.5E	-0.036	-0.971	-0.971	-0.971	26.5N	78.5E	0.107	-1.681	-1.681	-1.681
23.5N	74.5E	-0.049	-0.371	-0.371	-0.371	26.5N	79.5E	0.022	***-2.486***	***-2.486***	***-2.486***
23.5N	75.5E	**0.218**	-0.608	0.017	-1.16	26.5N	80.5E	-0.144	-1.57	-1.57	-1.57
23.5N	76.5E	0.152	-1.302	-1.302	-1.302	26.5N	81.5E	-0.128	-1.413	-1.413	-1.413
23.5N	77.5E	-0.029	1.065	1.065	1.065	27.5N	74.5E	**0.401**	-1.349	0.015	-1.176
23.5N	78.5E	-0.018	-0.339	-0.339	-0.339	27.5N	75.5E	0.181	-1.199	-1.199	-1.199
23.5N	79.5E	**-0.344**	-0.813	0.061	-1.239	27.5N	76.5E	0.105	-1.933	-1.933	-1.933
23.5N	80.5E	-0.177	-0.687	-0.687	-0.687	27.5N	77.5E	0.144	***-2.178***	***-2.178***	***-2.178***
24.5N	72.5E	-0.144	-0.915	-0.915	-0.915	27.5N	78.5E	-0.1	-0.955	-0.955	-0.955
24.5N	73.5E	0.066	-0.229	-0.229	-0.229	27.5N	79.5E	-0.072	-1.665	-1.665	-1.665
24.5N	74.5E	-0.203	-0.734	0.01	-0.734	27.5N	80.5E	0.062	***-2.075***	***-2.075***	***-2.075***
24.5N	75.5E	-0.084	-0.592	-0.592	-0.592	28.5N	75.5E	0.145	0.039	0.039	0.039
24.5N	76.5E	-0.041	0.024	0.024	0.024	28.5N	76.5E	0.071	-0.174	-0.174	-0.174
24.5N	77.5E	-0.217	-0.418	-0.418	-0.418	28.5N	77.5E	-0.025	-1.247	-1.247	-1.247
24.5N	78.5E	-0.211	-1.176	-1.176	-1.176	28.5N	78.5E	**0.211**	**-3.717**	**-3.717**	**-3.764**
24.5N	79.5E	-0.224	0.103	0.103	0.103	29.5N	76.5E	0.169	-1.618	-1.618	-1.618
24.5N	80.5E	**-0.371**	-0.418	-0.418	-0.718	29.5N	77.5E	0.13	***-3.306***	***-3.306***	***-3.306***
24.5N	81.5E	-0.21	0.86	0.86	0.86	29.5N	78.5E	0.125	***-2.044***	***-2.044***	***-2.044***
25.5N	73.5E	-0.149	-0.166	-0.166	-0.166	30.5N	76.5E	-0.123	0.055	0.055	0.055
25.5N	74.5E	0.04	0.229	0.229	0.229	30.5N	77.5E	**0.593**	-1.223	0.013	-1.381
25.5N	75.5E	0.202	***-2.951***	***-2.951***	***-2.951***	30.5N	78.5E	**0.444**	**-2.517**	0.046	**-1.996**
25.5N	76.5E	**0.227**	-1.586	-1.586	**-1.996**	31.5N	76.5E	**0.281**	-1.428	0.015	-1.507
25.5N	77.5E	**-0.255**	-0.039	-0.039	-0.481	31.5N	77.5E	**-0.253**	-1.081	-1.081	-1.87
25.5N	78.5E	**-0.272**	-1.207	0.009	**-2.123**	31.5N	78.5E	**0.395**	**2.888**	0.04	1.728
25.5N	79.5E	-0.247	-1.192	-1.192	-1.192	31.5N	79.5E	**0.475**	1.476	-0.013	0.245
25.5N	80.5E	**-0.409**	-0.797	-0.034	-1.097						

r_1 = lag-1 SC, Z-MK = Mann-Kendall's Z-statistics, Org = original MK test, Mod = modified MK test, PW = MK test with pre-whitening of data

Table 6. Lag-1 Serial Correlation and Mann-Kendall's Z-Statistics of OEM of the Yamuna River Basin [$r_1(l)$ = -0.248 and $r_1(u)$ = 0.208]

Grid Station		r_1	Z-MK			Grid Station		r_1	Z-MK		
Lat	Long		Org	Mod	PW	Lat	Long		Org	Mod	PW
21.5N	75.5E	0.099	1.320	1.321	1.321	25.5N	81.5E	0.020	***2.647***	***2.648***	***2.648***
22.5N	74.5E	0.084	1.785	1.785	1.785	25.5N	82.5E	-0.118	1.358	1.359	1.359
22.5N	75.5E	0.050	1.335	1.335	1.335	26.5N	73.5E	0.042	-1.153	-1.154	-1.154
22.5N	76.5E	0.028	***1.990***	***1.991***	***1.991***	26.5N	74.5E	0.172	0.569	0.569	0.569
22.5N	77.5E	0.001	0.917	0.918	0.918	26.5N	75.5E	0.155	***2.559***	***2.559***	***2.559***
22.5N	78.5E	0.168	***2.354***	***2.356***	***2.356***	26.5N	76.5E	-0.036	***1.991***	***1.993***	***1.993***
22.5N	79.5E	**0.234**	**2.110**	**2.111**	1.184	26.5N	77.5E	0.144	***3.002***	***3.003***	***3.003***
23.5N	73.5E	0.117	***3.776***	0.056	***3.777***	26.5N	78.5E	-0.188	***2.606***	***2.607***	***2.607***
23.5N	74.5E	0.035	***2.678***	***2.679***	***2.679***	26.5N	79.5E	0.085	***3.502***	***3.507***	***3.507***
23.5N	75.5E	**0.323**	**2.472**	**2.473**	1.097	26.5N	80.5E	-0.065	***2.141***	***2.141***	***2.141***
23.5N	76.5E	-0.136	1.517	1.519	1.519	26.5N	81.5E	-0.194	0.924	0.924	0.924
23.5N	77.5E	**-0.291**	1.146	0.031	0.963	27.5N	74.5E	-0.007	0.079	0.079	0.079
23.5N	78.5E	-0.101	1.406	1.407	1.407	27.5N	75.5E	0.032	1.193	1.193	1.193
23.5N	79.5E	0.014	1.763	1.766	1.766	27.5N	76.5E	-0.069	0.371	0.372	0.372
23.5N	80.5E	0.037	***2.433***	***2.433***	***2.433***	27.5N	77.5E	0.003	***3.270***	***3.271***	***3.271***
24.5N	72.5E	0.074	***1.998***	***1.999***	***1.999***	27.5N	78.5E	-0.025	***3.341***	***3.343***	***3.343***
24.5N	73.5E	-0.097	1.240	1.241	1.241	27.5N	79.5E	0.026	1.808	1.808	1.808
24.5N	74.5E	**0.307**	**3.658**	0.020	**1.965**	27.5N	80.5E	-0.141	1.011	1.012	1.012
24.5N	75.5E	**0.320**	**2.441**	-0.025	1.515	28.5N	75.5E	0.046	1.125	1.131	1.131
24.5N	76.5E	-0.043	1.651	1.652	1.652	28.5N	76.5E	-0.100	0.537	0.537	0.537
24.5N	77.5E	0.019	***3.792***	***3.793***	***3.793***	28.5N	77.5E	-0.153	0.134	0.134	0.134
24.5N	78.5E	0.051	***3.160***	***3.162***	***3.162***	28.5N	78.5E	0.194	***4.447***	0.000	***4.448***
24.5N	79.5E	0.136	***3.106***	***3.108***	***3.108***	29.5N	76.5E	-0.047	1.047	1.096	1.096
24.5N	80.5E	0.004	***2.782***	***2.786***	***2.786***	29.5N	77.5E	-0.071	1.936	1.937	1.937
24.5N	81.5E	0.167	2.938	2.939	2.939	29.5N	78.5E	0.024	0.672	0.673	0.673
25.5N	73.5E	-0.157	0.537	0.538	0.538	30.5N	76.5E	0.009	1.698	1.699	1.699
25.5N	74.5E	-0.106	1.509	1.509	1.509	30.5N	77.5E	0.051	***2.156***	***2.157***	***2.157***
25.5N	75.5E	0.115	***2.566***	***2.566***	***2.566***	30.5N	78.5E	0.118	0.387	0.387	0.387
25.5N	76.5E	0.030	***2.812***	***2.813***	***2.813***	31.5N	76.5E	0.158	***2.267***	***2.268***	***2.268***
25.5N	77.5E	0.030	***2.173***	***2.174***	***2.174***	31.5N	77.5E	0.115	1.216	1.216	1.216
25.5N	78.5E	0.096	***3.238***	***3.239***	***3.239***	31.5N	78.5E	-0.056	-0.348	-0.348	-0.348
25.5N	79.5E	-0.104	***3.100***	***3.107***	***3.107***	31.5N	79.5E	-0.035	0.963	0.963	0.963
25.5N	80.5E	0.014	***2.964***	***2.966***	***2.966***						

r_1 = lag-1 SC, Z-MK = Mann-Kendall's Z-statistics, Org = original MK test, Mod = modified MK test, PW = MK test with pre-whitening of data

Table 7. Summary of Trend Analysis Based on Modified Mann-Kendall Test

S. No	Variable	Mean Value			No. of Series Indicating significant lag-1 serial correlation	No. of Series Indicating Significant			
		Spatial mean	Range	SD		Rising Trend	Falling Trend	No Trend	Overall Trend
1	Annual rainfall	893.3	372.2-1653.5	280.3	13		6 (8)	59 (57)	- ve
2	Monsoon rainfall	806.8	327.0 - 1568.9	259.7	12		8 (13)	57 (52)	- ve
3	Non-monsoon rainfall	86.5	19.5 - 479.0	100.1	13	3 (2)		62 (63)	+ ve
4	Annual rainydays	88	46.0 - 160.0	25	17	4 (2)	7 (11)	54 (52)	- ve
5	Monsoon rainydays	70	43 - 96	15	5		5 (6)	60 (59)	- ve
6	Non-monsoon rainydays	17	1 - 72	14	22	6 (2)	1 (2)	58 (61)	+ ve
7	OEM	190	173 - 207	7	4	29 (30)		36 (35)	+ ve
8	Aridity Index (AI)	38.0	14.9 - 74.6	12.9	13		6 (8)	59 (57)	- ve

(Values in the parenthesis are the results from Mann-Kendall with pre-whitening test)

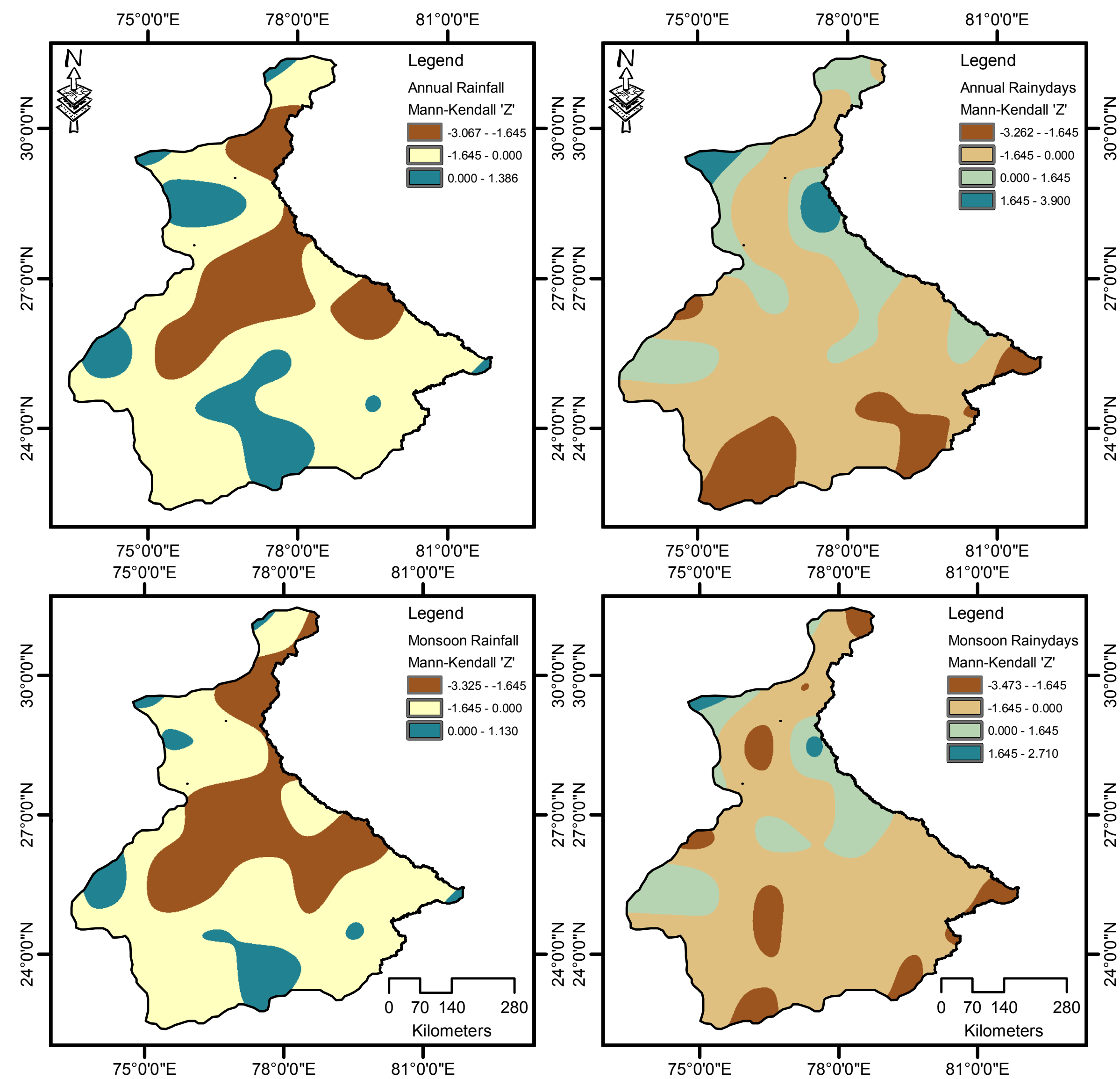

Fig. (6). contd….

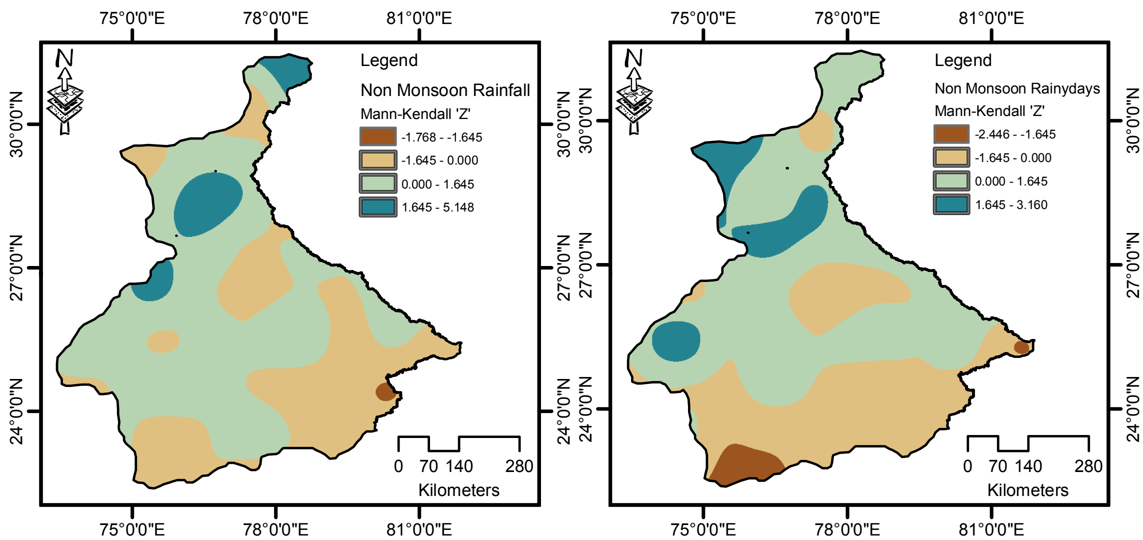

Fig. (6). Spatial distribution pattern of Mann-Kendall's Z-statistics of rainfall (annual, monsoon & non-monsoon) and rainydays (annual, monsoon & non-monsoon).

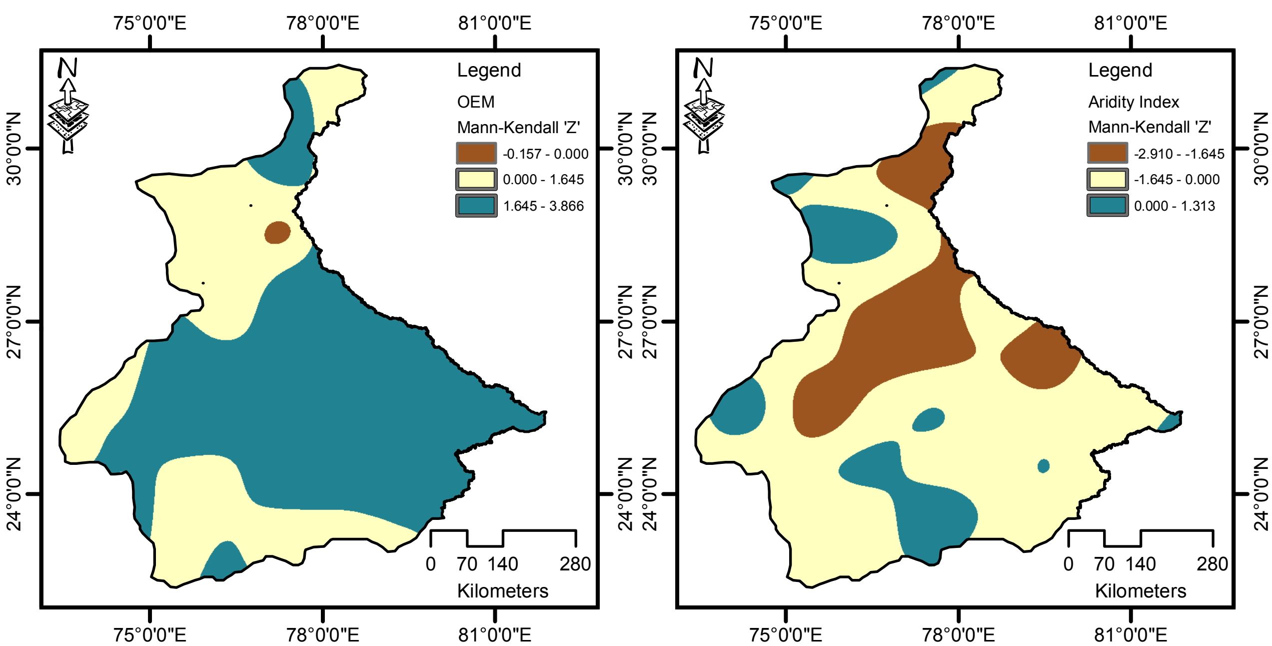

Fig. (7). Spatial distribution pattern of Mann-Kendall's Z-statistics of OEM and aridity index.

annual rainfall pattern and annual rainydays, and monsoon rainfall and monsoon rainydays were -0.832 and -0.362, and -0.874 and -0.62, respectively. On the other hand magnitude of non-monsoon rainfall has been insignificantly increased though few grid data show the significant rising trend in the north and north-west portion of the basin, which can be evident from the average Z-statistic of +0.209 and +0.258 for non-monsoon rainfall and rainydays was, respectively. Spatial distribution pattern of rainydays are more or less similar to the rainfall. Most of the area in the central to South-east and central to south experiences declination in the rainfall. Since, OEM is dependent on the rainfall pattern and potential evapotranspiration, and both the variable has shown a general falling trend in the basin. Therefore, increasing trend in the OEM was the resulting effect of the rainfall and evapotranspiration pattern. The overall mean Z-statistic for the OEM was +1.81. Similarly, aridity index is the ratio of annual rainfall and potential evapotranspiration. Falling trend observed in the aridity index is associated with the overall falling trend in the rainfall pattern of the Yamuna River basin (Table **7** and Fig. **6**). The overall mean Z-statistic value for the in aridity index was -0.78. Based on the trend analysis, it can be stated that the water resources potential of the Yamuna River basin is declining.

Periodicity

Significance of the spectral estimates was evaluated at 90 and 95 percent confidence levels of the appropriate null continuum (red or white noise). The relationship between the correlogram and spectral estimates are shown in Fig. (**8**) for sample time series of annual rainfall of the Yamuna river basin. If a time series has persistence, the spectrum changes over all the wavelengths and the amplitude of the spectrum has a decreasing trend from long to short wavelengths (i.e. corresponding to increasing order of lags); and the spectrum is termed as 'red noise' (Fig. **8a**). For the spectrum of a time series having persistence with necessary exponential relationship between r_1, r_2 and r_3 (i.e. Markov-type persistence), the appropriate null appropriate null hypothesis was assumed to be a Markov red noise continuum (Fig. **8b**). A series characterized by an insignificant positive lag-1 SC or a series that has a significant positive lag-1 SC but not a simple Markov-type, and any series with negative lag-1 serial correlation coefficient was evaluated as a white noise continuum (Fig. **8c** and **8d**). From Fig. (**8d**), it may be stated that times series with negative lag-1 SC shows the high frequency variability (i.e. L = 14, and $P = 2m/L$ = 2.4 years). For all the variables, power spectrum plots and the tables were prepared. However, for presentation, power spectrum plots of monsoon rainfall, OEM and AI are given (Figs. **9** through **11**). To evaluate the power spectrum results, generally period values were computed using eq (26) (i.e. $P = 2m/L$) for all the time series. The computed values of period along with their significance level for monsoon rainfall, rainydays and OEM are given in Tables **1** through **3**. Tables **1** - **3** also comprised of the serial correlation coefficients up to lag-3. Analysis revealed that the short-term period fluctuation of 2.0 to 4.9 years is dominant in the annual and monsoon rainfall, whereas, medium and long-term period of 5.0 to 34.0 years is dominant in case of non-monsoon rainfall. This short term periodic behavior (high frequency) of rainfall pattern in the Yamuna river basin should be kept in mind while preparing the water resources plan. In case of number of rainydays, the long-period is dominated over the short-periodicity. Results of the power spectrum analysis of OEM and AI indicated that OEM and AI have dominating short-period fluctuations of 2.0 to 3.0 years, which leads to high probability of meteorological and agricultural drought and

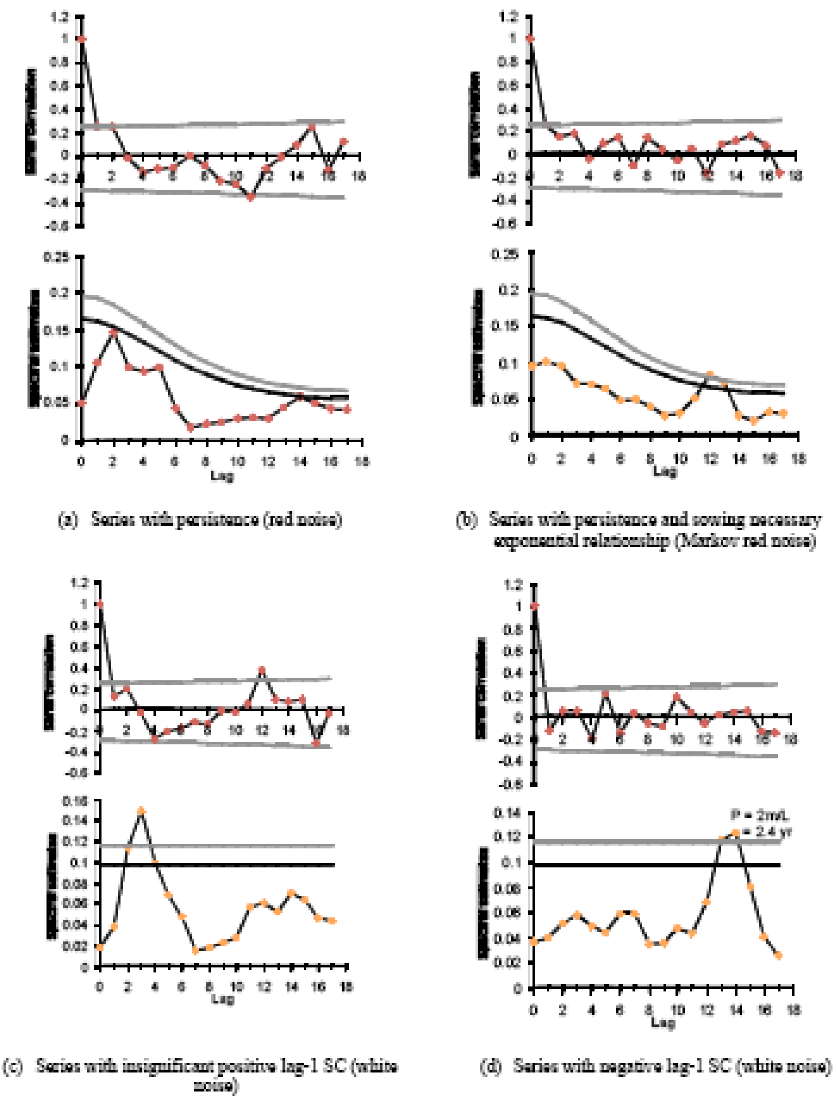

Fig. (8). Relation between correlogram and spectral estimates.

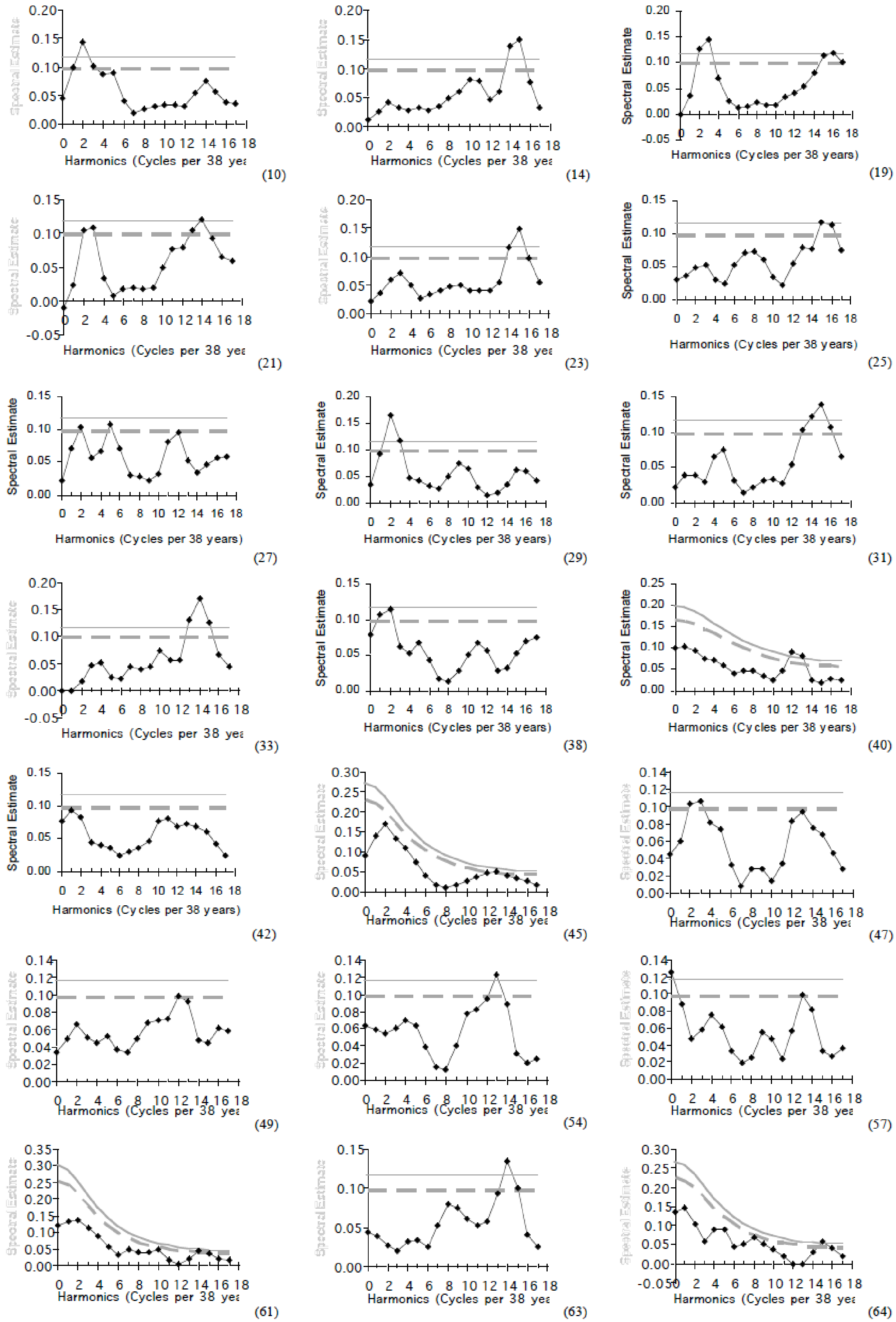

Fig. (9). Power spectrum plot for monsoon rainfall (——: 95 % confidence limit; – – – –: 90 % confidence limit).

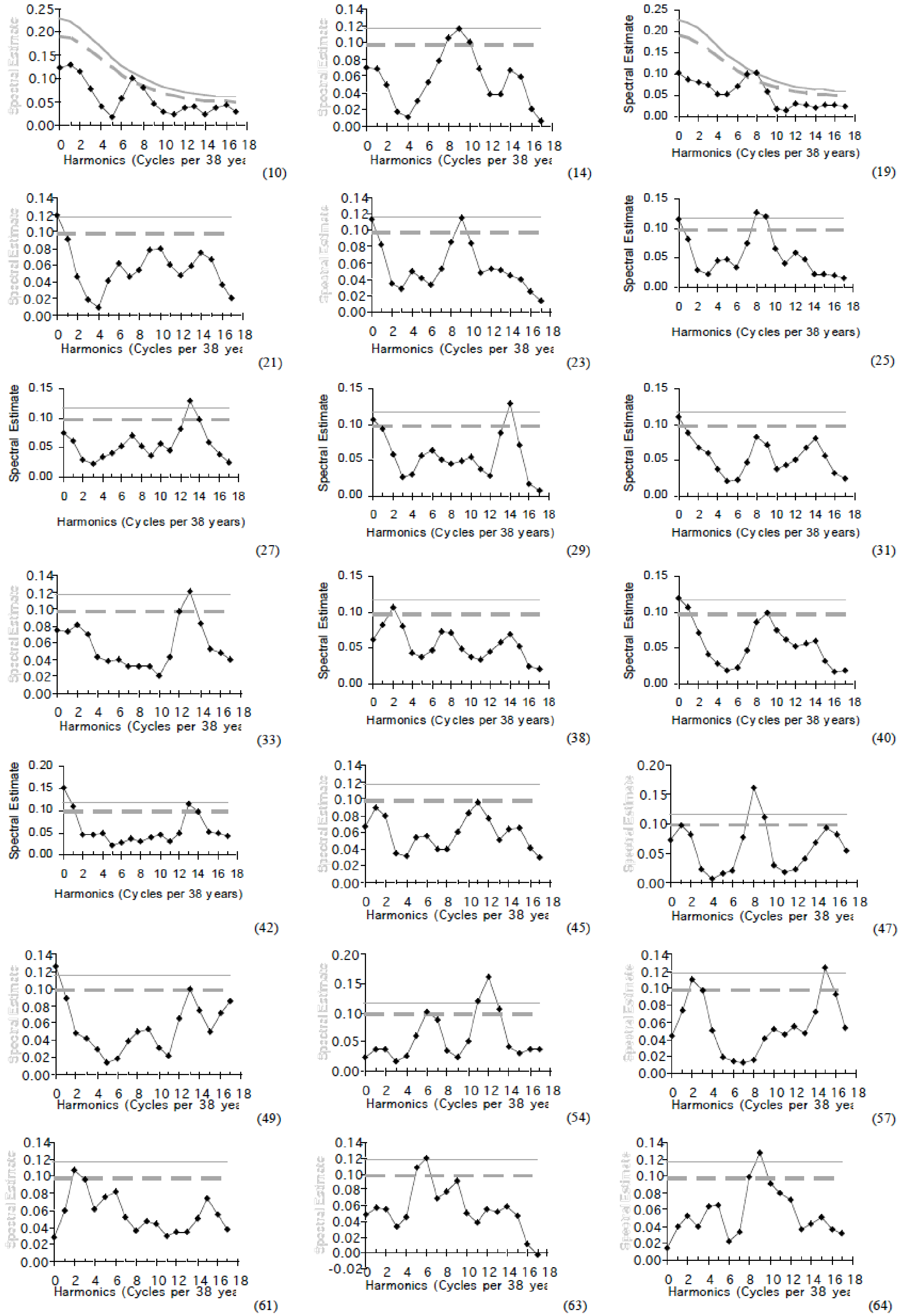

Fig. (10). Power spectrum plot for OEM (——: 95 % confidence limit; – – – –: 90 % confidence limit).

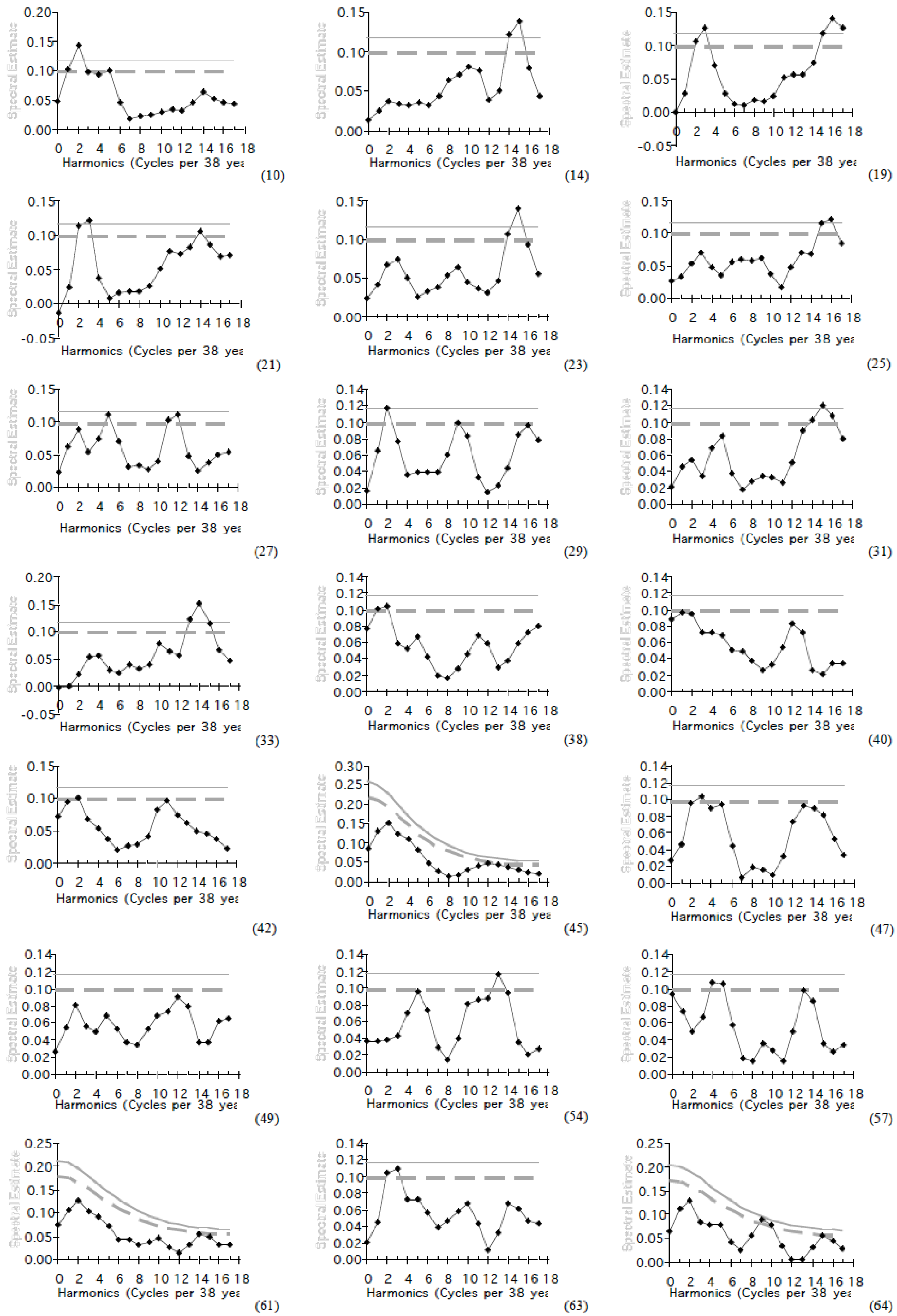

Fig. (11). Power spectrum plot for aridity index (AI) (——: 95 % confidence limit; – – – –: 90 % confidence limit).

will frequently disturbs the planning of *Kharif* crops in the Yamuna river basin.

CONCLUSIONS

Based on the analysis, following conclusion can be drawn;

(i) There is a considerable difference in the monsoon and non-monsoon rainfall pattern in terms of persistence and periodicity.

(ii) Approximately 20 percent rainfall time series show the presence of persistence characterized by lag-1 serial correlation.

(iii) Presence of serial correlation in the time series significantly affects the Mann-Kendall's trend analysis.

(iv) Original Mann-Kendall test overestimate the presence of significant trend in the series than the modified Mann-Kendall and Mann-Kendall with Pre-whitening tests. Based on the overall trend results, the original Mann-Kendall test resulted approximately 37 % more presence of significant trend than the modified Mann-Kendall test.

(v) Overall falling trend was observed in the annual rainfall, monsoon rainfall, annual rainydays, monsoon rainydays, and AI. In sixty five grid locations, spatial mean of Mann-Kendall's Z-statistics for annual rainfall and monsoon rainfall were -0.832 and -0.874, respectively. Regardless of few series having significant trend, most of the series have higher values of Z-statistic.

(vi) An increasing trend with overall mean Z-statistic of +1.81 was observed in OEM which shows the gradual delay in the onset of effective monsoon in the Yamuna river basin.

(vii) It may be remarked that the declining monsoon rainfall and number of monsoon rainydays along with the delay in the onset of effective monsoon (i.e. rising trend in OEM) will be the great concern while preparing the river basin management plan.

(viii) It was observed that high frequency fluctuations associated with short-period cycle is dominating over the basin for annual and monsoon rainfall, OEM and AI. However, for non-monsoon rainfall low frequency fluctuations were identified.

(ix) There was a good consistency between the lag-1 serial correlation and results of the power spectrum analysis. Positive lag-1 serial correlation coefficients gives low frequency fluctuations, whereas negative is an indicator for the high frequency (Fig. **8**).

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