Long term spatial and temporal rainfall trends and homogeneity analysis in Wainganga basin, Central India

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Gridded rainfall data of 0.5 × 0.5° resolution (CRU TS 3.21) was analysed to study long term spatial and temporal trends on annual and seasonal scales in Wainganga river basin located in Central India during 1901–2012. After testing the presence of autocorrelation, Mann–Kendall (Modified Mann–Kendall) test was applied to non-auto correlated (auto correlated) series to detect the trends in rainfall data. Theil and Sen’s slope estimator test was used for finding the magnitude of change over a time period. For detecting the most probable change year, Pettitt–Mann–Whitney test was applied. The rainfall series was then divided into two partial duration series for finding changes in trends before and after the change year. Arc GIS was used to explore spatial patterns of the trends over the entire basin. Though most of the grid points shows a decreasing trend in annual rainfall, only seven grids has a significant decreasing trend during 1901–2012. On the basis of seasonal trend analysis, non-significant increasing trend is observed only in post monsoon season while seven grid points show significant decreasing trend in monsoon rainfall and non-significant in pre-monsoon and winter rainfall over the last 112 years. During the study period, overall a 8.45% decrease in annual rainfall is estimated. The most probable year of change was found to be 1948 in annual and monsoonal rainfall. There is an increasing rainfall trend in the basin during the period 1901–1948, which is reversed during the period 1949–2012 resulting in decreasing rainfall trend in the basin. Homogeneous trends in annual and seasonal rainfall over a grid points is exhibited in the basin by van Belle and Hughes’ homogeneity trend test.

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1. Introduction

Rainfall is one of the key climatic variables that affect both the spatial and temporal patterns of water availability. One of the challenges posed by climate change/climate variability is ascertaining, identification and quantification of trends in rainfall and their implications on river flows in order to assist in formulation of adaptation measures through appropriate strategies for water resources management. It is also recognised that rainfall is one of the key climatic variables that affect both the spatial and temporal patterns on water availability (De Luis et al., 2000).

In the analysis of trends of rainfall in the Indian Himalayas, Basistha et al. (2009) observed that rainfall has decreased in the Indian Himalayas during last century as a sudden shift, rather than gradual trend. Kumar and Jain (2011) found decreasing trend in the annual rainfall and rainy days in 15 basins out of 22 basins in India. Even, consolidation of recent studies that have been carried out on analysis of rainfall which is the key input into the hydrologic system, there is conclusive evidence that rainfall is decreasing in Asia (Sinha Ray and Srivastava, 1999; Khan et al., 2000; Shrestha et al., 2000; Mirza, 2002; Lal, 2003; Min et al., 2003; Goswami et al., 2006; Dash et al., 2007). Some investigators (i.e. Cayan and Peterson, 1989; Lins and Slack, 1999; Jain and Lall, 2000) have reported evidence of trends (possibly due to anthropogenic influences) and long-term variability of climate. Studies suggest South Asia most vulnerable to climate change.

Analysis of rainfall trends is important in studying the impacts of climate change for water resources planning and management (Haigh, 2004). It has been recognised that global or continental scale observations of historical climate are less than useful for local or regional scale planning (Barsugli et al., 2009; Brekke et al., 2009; Raucher, 2011). Thus, the evaluation of historical trends or future projections on a regional or local scale is needed. In this study, an attempt has therefore been made to study the trends in the annual rainfall series in the Wainganga basin, India to find if there have been any significant changes in the rainfall trends during 1901–2012.

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2. Study area and data used

2.1. Study area

Wainganga basin is a sub-basin of the Godavari River basin which is located from 78°00′ to 81°00′ East longitudes and 19°00′–22°07′ North latitudes as shown in Fig. 1. The total catchment area of the basin is 51,421 km² with an elevation ranges from 144 to 1208 m (Fig. 1) above mean sea level. The basin is bounded in the North by Central India hills, in the South and East by the Eastern Ghats and in the West by Maikala hill range. The Chiroli Hills form the watershed dividing the Wainganga basin.
from the Narmada basin. It is a typical basin considered from geographical and geological point of view covering major parts of the states Maharashtra (27,350 km²), Madhya Pradesh (23,109 km²) and small portions of Chhattisgarh states (962 km²). The river in its initial reaches flows westwards and thereafter turns southwards in Madhya Pradesh and continues to flow Southwards through the Maharashtra State.

The climate of the basin is characterised as summer from March to May with monsoon season from June to September having some rains in post monsoon season too. Mean daily maximum temperature varies from 26–30 °C in July to 32–33 °C in October. The minimum temperatures are observed in the month of January in the range of 10–15 °C witnessing the winter season. The water users in Wainganga sub basin face many challenges to manage their water resources. Flooding has been a major problem in the past. Though most parts of the basin receives a rainfall of about 150 cm during the monsoon months, there are very few water conservation structures on the main river, and therefore only a few irrigation schemes exists in the basin.

2.2. Data used

CRU TS 3.21 dataset comprises more than 4000 weather stations distributed around the world. The data set contain nine climatic variables: cloud cover, diurnal temperature range, frost day frequency, rainfall, daily mean temperature, monthly average daily maximum temperature, vapour pressure, Potential Evapotranspiration and wet day frequency. However in this study only rainfall data for the period 1901–2012 at 0.5° × 0.5° resolution was used. The data was downloaded from Centre of Environmental Data Archival (http://badc.nerc.ac.uk). Eighteen grid points of CRU TS 3.21 dataset cover the whole Wainganaga basin as seen in Fig. 1.

3. Methodology

Annual series was prepared for each grid and annual scale trend analysis was performed. The monthly rainfall data was divided into four seasons: Monsoon season (June to September), post-monsoon season (October and November), pre-monsoon season (March to May) and cold winter season (December–February) for seasonal analysis. After fixing the most probable change point, the trend analysis was performed on two partial duration series before and after the change point.

![LOWESS regression lines for annual rainfall in Wainganga basin (Pred means prediction).](image1)

![LOWESS regression lines for seasonal rainfall in Wainganga basin (Pred means prediction).](image2)
has more than 2 series showing 10% changes. MMK values in bold represents presence of autocorrelation in rainfall series. Negative/positive magnitude of a trend was estimated by Theil and Sen's slope estimator test (Appendix C).

### Table 1
Result of MK (MMK) test (at 5% level) and percentage change over 1901–2012 with autocorrelation.

| Grids | Seasonal | Annual | Z-value | % change | Monsoon | Z-value | % change | Post-Monsoon | Z-value | % change | Pre-Monsoon | Z-value | % change | Winter | Z-value | % change |
|-------|----------|--------|---------|----------|---------|---------|----------|--------------|---------|----------|------------|---------|----------|--------|---------|----------|
| 1     |          | 1.33   | 9.35    | 1.80     | 12.79   | -0.39   | -9.54    | 0.17         | 3.33    | -1.78    | 35.86      |
| 2     |          | -0.03  | -0.13   | 0.29     | 2.01    | -0.05   | -1.93    | -0.07        | 1.48    | -1.85    | 37.05      |
| 3     |          | -1.82  | -12.70  | -1.77    | -12.98  | 0.26    | 4.38     | -0.02        | -0.36   | -1.38    | 26.97      |
| 4     |          | 0.44   | 2.21    | 0.93     | 6.11    | -0.65   | -12.63   | 0.08         | 1.48    | -1.26    | 24.06      |
| 5     |          | -0.58  | -3.56   | -0.41    | -2.23   | -0.34   | -6.20    | -0.18        | -3.01   | -1.27    | 23.51      |
| 6     |          | -1.97  | -13.39  | -2.20    | -14.59  | 0.41    | 7.99     | -0.66        | 14.77   | 0.08     | 19.39      |
| 7     |          | -0.74  | -1.77   | -0.37    | -2.29   | -0.90   | -17.43   | 0.05         | 0.60    | -0.53    | 10.97      |
| 8     |          | -2.00* | -9.98   | -1.51    | -8.32   | -0.01   | -0.13    | -1.11        | 23.76   | -1.28    | 26.01      |
| 9     |          | -1.97  | -11.78  | -1.66    | -10.87  | 0.90    | 16.01    | -1.46        | 34.45   | -1.34    | 27.41      |
| 10    |          | -1.76  | -10.43  | -1.52    | -9.04   | 0.85    | 16.98    | -1.07        | 22.88   | -1.60    | 28.78      |
| 11    |          | -1.23  | -5.54   | -0.98    | -4.62   | 0.88    | 18.07    | -0.11        | -2.52   | -0.92    | 19.55      |
| 12    |          | 0.02   | 0.43    | 0.15     | -0.79   | 0.80    | 17.42    | 1.11         | 18.76   | -0.83    | 18.01      |
| 13    |          | -1.86  | -8.56   | -1.30    | -7.24   | -0.58   | -12.54   | -0.52        | -9.09   | -1.23    | 21.59      |
| 14    |          | -2.63* | -13.09  | -2.24    | -12.14  | 0.42    | 7.58     | -1.36        | 31.49   | -1.53    | 32.23      |
| 15    |          | -2.34  | -13.72  | -2.12    | -12.98  | 0.88    | 15.51    | -1.41        | 31.45   | -1.49    | 28.71      |
| 16    |          | -2.19  | -12.63  | -1.98    | -12.10  | 0.80    | 16.93    | -1.42        | 30.96   | -1.33    | 26.17      |
| 17    |          | -0.08  | -1.03   | 0.00     | 0.00    | 1.49    | 30.55    | 0.37         | 7.97    | 0.46     | 2.48       |
| 18    |          | -2.94  | -15.64  | -2.71    | -15.58  | 0.83    | 16.06    | -1.51        | -32.69  | -1.69    | 36.32      |

MMK values in bold represents presence of autocorrelation in rainfall series. Negative/positive Z value indicates decreasing/increasing trend. Shaded cells show that a grid has more than 2 series showing 10% changes.

* Represents significant trend.

The following tests were used for carrying out the rainfall trend analysis:

1. Significance of autocorrelation was detected by using student's t test at lag-1 in annual and seasonal rainfall series (Appendix A).
2. Mann–Kendall (MK)/Modified Mann–Kendall (MMK) tests were applied to the non-autocorrelated/autocorrelated series to detect the presence of trend in annual and seasonal rainfall (Appendix B).
3. Magnitude of a trend was estimated by Theil and Sen's slope estimator test (Appendix C).
4. Changes were calculated as percentage change over the period of 112 year in annual and seasonal rainfall series (Appendix D).
5. Pettitt Mann–Whitney (PMW) test was applied to detect most probable change year in the annual and monsoonal rainfall series (Appendix E).
6. Percentage change in rainfall over a mean was calculated on the basis of change year in annual and monsoonal rainfall series.
7. Inverse distance weighted interpolation technique was used to explore spatial temporal rainfall trend over a basin with the help of Arc GIS.
4. Results

4.1. Preliminary analysis

Preliminary analysis of the rainfall data shows that mean annual rainfall varies from 1097 mm in western part (Grid #1) to 1541 mm in the eastern part (Grid #16).

The standard deviation varies from 186.03 mm to 282.2 mm for Grid #12 and #9, respectively. The skewness varies between 0.09 and 0.36, predominantly positive skewness with average around 0.21 indicating that annual rainfall during the period is asymmetric and it lies to the right of the mean over all the stations. Kurtosis varies from 1.40 to 4.88 with an average around 3.26. The coefficient of variation (CV) varies between 16.04% (Grid #13) and 21.46% (Grid #9) with an average coefficient of variation 20.97% in the entire basin. Preliminary analysis of the rainfall concluded that the zones of usually heavy rainfall are the zones of least variability and zones of lower rainfall are the zone of higher variability.

Fig. 2a and b represents the spatial mean annual and mean monsoon rainfall variation over Wainganga basin. Spatial distribution of annual rainfall map shows annual decrease in rainfall from Grid #14 (North East) to Grid #1 (North West) and Grid #12 (South West). In monsoon season, Grid #14 receives more rainfall while Grid #17 less.

4.2. Exploratory data analysis

The running mean is not resistant to (robust) to local fluctuations. Therefore, to reduce the local fluctuations, the annual and seasonal data series are fitted with LOWESS (Cleveland, 1979, 1984; Helsel and Hirsch, 2002) regression curves to identify patterns over time. The LOWESS regression curve, as seen in Fig. 3, indicates increasing pattern in the rainfall upto 1930 in annual series and a decreasing trend thereafter. Fig. 4 shows the LOWESS regression curves for Seasonal rainfall series depicting more or less the same patterns. From Fig. 4 it can be seen that monsoon rainfall series has followed similar trend to annual rainfall series. Post monsoon rainfall has shown steep increasing trend up to 1940 after which it decreases gradually. Pre monsoon rainfall series has shown significant trend, increasing marginally throughout the century. Winter rainfall series has shown no significant trend in the first half but steep decreasing after 1980s.

4.3. Annual and seasonal scale rainfall trend analysis during 1901–2012

The results of the autocorrelation analysis for 1901–2012 are presented in Table 1 along with Z statistics of MK/MMK test. Statistically, only two annual series were autocorrelated at 5% significance level and five seasonal rainfall series: Grid #17 data is autocorrelated on annual as well as seasonal scale. Most of the annual series exhibits a decreasing trend, out of which only seven has significant decreasing trend except Grid #1, 4 and 12 with non-significant increasing trend. On the basis of seasonal trend analysis, non-significant increasing trend is observed only in post monsoon season while seven grid points show significant decreasing trend in monsoon rainfall and non-significant decreasing trends in pre-monsoonal and winter rainfall over 112 years (at the 5% level). Table 1 also shows the percentage changes over mean values in annual and seasonal rainfall. Shaded grids shows more than 10% changes in two series and darker shades means more number of series. Grids #9, #10, #15, #16 and #18 shows maximum series (i.e. 5) showing 10% changes. All grids shows non-significantly decrease in magnitude of change in rainfall during the winter season.

Fig. 5(a and b) shows Grid #1 and #18 with highest rising and falling trends in annual and monsoon rainfall at 5% significance respectively have been identified as the two poles in the rain ganga basin with respect to trend. Spatially, the falling trend observed at Grid #18 is found to slowly transform to rising trend in Grid #1and #12 through the intermediate grids lying between two poles.

(8) Homogeneity in annual series was tested by Pettitt’s test, SNHT test and Buishand’s test (Appendix F).

(9) Homogeneity in trends was tested by van Belle and Hughes’ homogeneity trend test to obtain global trend over a basin (Appendix F).

### Table 2

Most probable change year by PMW test, Pettitt’s test, SNHT test and Buishand’s test.

| Grid | PWM | Pettitt’s test | SNHT | Buishand’s test |
|------|-----|---------------|------|----------------|
|      | Year | Prob. | K value | Year | Trend | T Satoshi | Year | Trend | Q value | Year | Trend |
| 1    | 1930 | 91.27  | 759     | 1930 | Ho    | 6.75     | 1930 | Ho    | 12.23   | 1930 | Ho    |
| 2    | 1930 | 53.28  | 424     | 1930 | Ho    | 2.85     | 1904 | Ho    | 7.37    | 1930 | Ho    |
| 3    | 1949 | 97.89  | 955     | 1949 | Ha    | 7.71     | 1949 | Ho    | 14.64   | 1949 | Ha    |
| 4    | 1925 | 77.88  | 597     | 1925 | Ho    | 6.22     | 1909 | Ho    | 5.04    | 1925 | Ho    |
| 5    | 1964 | 73.48  | 560     | 1964 | Ho    | 3.57     | 1902 | Ho    | 7.53    | 1964 | Ho    |
| 6    | 1949 | 97.24  | 921     | 1949 | Ha    | 6.74     | 1949 | Ho    | 13.69   | 1949 | Ho    |
| 7    | 1970 | 92.54  | 783     | 1970 | Ho    | 4.72     | 1971 | Ho    | 11.14   | 1970 | Ho    |
| 8    | 1971 | 98.18  | 973     | 1971 | Ha    | 5.76     | 1963 | Ho    | 12.65   | 1963 | Ho    |
| 9    | 1947 | 95.66  | 561     | 1947 | Ho    | 7.10     | 1942 | Ho    | 13.71   | 1944 | Ho    |
| 10   | 1947 | 92.34  | 779     | 1947 | Ho    | 4.64     | 1963 | Ho    | 11.36   | 1963 | Ho    |
| 11   | 1963 | 89.06  | 723     | 1963 | Ho    | 2.99     | 1963 | Ho    | 9.12    | 1963 | Ho    |
| 12   | 1964 | 56.91  | 446     | 1964 | Ho    | 2.93     | 1926 | Ho    | 7.88    | 1926 | Ho    |
| 13   | 1971 | 99.51  | 1121    | 1971 | Ha    | 7.70     | 1971 | Ho    | 14.21   | 1971 | Ha    |
| 14   | 1948 | 99.36  | 1092    | 1948 | Ha    | 8.63     | 1948 | Ho    | 15.50   | 1948 | Ha    |
| 15   | 1947 | 98.66  | 1009    | 1947 | Ha    | 8.63     | 1947 | Ho    | 15.42   | 1947 | Ha    |
| 16   | 1947 | 98.21  | 975     | 1947 | Ha    | 7.73     | 1947 | Ho    | 14.59   | 1947 | Ha    |
| 17   | 1994 | 41.52  | 356     | 1994 | Ho    | 1.10     | 1990 | Ho    | 3.20    | 1994 | Ho    |
| 18   | 1948 | 99.82  | 1224    | 1948 | Ha    | 11.57    | 1947 | Ha    | 17.88   | 1948 | Ha    |

Ha- Heterogeneous series, Ho-Homogenous series.
4.4. Grid-wise change point analysis

Table 2 shows result of change point probability in annual rainfall is computed using PWM test. Pettitt’s test, SNHT test and Buishand’s test were used to test the homogeneity of a rainfall series. The table depicts that year 1948 is found to be the most probable change year using PWM test. Homogeneity analysis also shows that 8 annual rainfall series are heterogeneous around the year 1948 – it means there is a significant change in the mean before and after the detected change point. SNHT test is known to find change point towards the beginning and end of the series whereas Buishand’s and Pettitt’s tests are sensitive to find the changes in the middle of a series (Martínez et al., 2009). The results given in Table 2 are in agreement with Martínez et al. (2009) conclusion showing most of the series homogenous.

An analysis across the tests shows that there are 6 common grids where all the tests are in agreement about the change point year. The changes in the mean of these series along with the rainfall plots are shown in Fig. 6(a) Grid #3, (b) Grid #13, (c) Grid #14, (d) Grid #15, (e) Grid #16 and (f) Grid #18 (μ1 and μ2 represents the mean rainfall before and after the change point).

Fig. 6. Change year in annual rainfall series (a) Grid #3, (b) Grid #13, (c) Grid #14, (d) Grid #15, (e) Grid #16 and (f) Grid #18 (μ1 and μ2 represents the mean rainfall before and after the change point).
because of its geographical setting leading to a different change point.

4.5. Rainfall trend analysis using two partial series for periods 1901–1948 and 1949–2012

The results of the autocorrelation analysis for 1901–1948 and 1949–2012 are presented in Tables 4 and 5 along with Z statistics of MK/MMK test, respectively. From table it is concluded that annual and seasonal series show significant increasing trend in the basin during the period 1901–1948 (Table 4), which turns decreasing during the period 1949–2012 (Table 5), showing an overall decreasing trend in the basin. Maximum % increasing change in annual rainfall is found at Grid #7 (28.18% during 1901–1948) and maximum decreasing % change in annual rainfall is found at Grid #17 (−11.05 during 1949–2012). Seasonal change in monsoon rainfall, approximately 80% of annual rainfall, is 24.44% at Grid #7 which is in agreement with the changes found in annual rainfall during 1901 to 1948. However, maximum seasonal changes during 1949–2012 in monsoon season are −5.55% at Grid #1, it is −4.92% at Grid #17 which are also in agreement with the annual rainfall data of that duration. All partial series, annual and seasonal during 1901–1948, at Grid #4, 5, 7 and #13 show that the changes are more than 10% in all the seasons shown in the darkest shade in Table 4. More than 10% changes are observed in post-monsoon, pre-monsoon and winter rainfall at these grid points (except Grid #12) during 1949–2012 shown in dark colour in Table 5.

4.6. Estimation of Manitude of trend slope in annual and seasonal rainfall series

The box-plots of Theil-Sen’s slopes for annual and seasonal rainfall series over the basin are shown in Fig. 7 for three time periods during 1901–2012, 1901–1948 and 1949–2012. At the annual scale, the median of slopes are located below the zero line, implying a decreasing trend over two spans i.e. 1901–1948 and 1949–2012, while monsoon season shows an increasing trend in second partial series. During 1901–1948, median of slopes of annual and seasonal series are located above zero line, indicating an increasing trend.

4.7. Analysis of homogeneity of trends

To test homogeneity of trends across annual and seasonal rainfall, van Belle and Hughes’ homogeneity trend test was applied on all the 18 grids in the basin. Results of the test are given in Table 6. With \( p = 18 \), the homogenous is found to be 4.11, 3.40, 0.22, 1.33 and 3.0 for annual, monsoon, post-monsoon, pre-monsoon and winter series respectively. At 5% significance level, null hypothesis of homogeneity of trends is accepted for annual and seasonal trends during 1901–1948 and 1949–2012. At the annual scale, the median of slopes are located below the zero line, implying a decreasing trend over two spans i.e. 1901–1948 and 1949–2012, while monsoon season shows an increasing trend in second partial series. During 1901–1948, median of slopes of annual and seasonal series are located above zero line, indicating an increasing trend.

Table 3
Change in percentage in the 1949–2012 mean over the 1901–48. The shaded rows are the grids where series are found heterogeneous using all the tests. Grids in bold face shows the change in the mean are more than 10%.

| Grid | Annual | Monsoon |
|------|---------|---------|
| 1    | 0.38    | 0.36    |
| 2    | 0.56    | 0.55    |
| 3    | 1.00    | 0.99    |
| 4    | 1.27    | 1.26    |
| 5    | 2.05*   | 2.04*   |
| 6    | 1.00    | 0.99    |
| 7    | 0.27    | 0.26    |
| 8    | 0.20*   | 0.19    |
| 9    | 0.45    | 0.44    |
| 10   | 0.56    | 0.55    |
| 11   | 0.44    | 0.43    |
| 12   | 0.27    | 0.26    |
| 13   | 0.72    | 0.71    |
| 14   | 1.27    | 1.26    |
| 15   | 0.70    | 0.69    |
| 16   | 0.63    | 0.62    |
| 17   | 0.38    | 0.37    |
| 18   | 1.06    | 1.05    |

Table 4
Result of MK (MMK) test (at 5% level) and percentage over 1901–48 with autocorrelation.

| Grid | Annual | Monsoon | Post-Monsoon | Pre-Monsoon | Winter |
|------|--------|---------|--------------|-------------|--------|
|      | Z-value  | % change | Z-value  | % change | Z-value  | % change | Z-value  | % change | Z-value  | % change |
| 1    | 2.50  | 2.44*   | 0.44  | 0.43*   | 0.34  | 0.33*   | 0.34  | 0.33*   | 0.34  | 0.33*   |
| 2    | 1.80  | 1.78    | 1.78  | 1.77    | 1.78  | 1.77    | 1.78  | 1.77    | 1.80  | 1.78    |
| 3    | 1.27  | 1.26    | 1.26  | 1.25    | 1.26  | 1.25    | 1.26  | 1.25    | 1.27  | 1.26    |
| 4    | 2.74  | 2.73    | 2.73  | 2.72    | 2.74  | 2.73    | 2.74  | 2.73    | 2.74  | 2.73    |
| 5    | 2.05* | 2.00*   | 2.00* | 2.00*   | 2.37* | 2.37*   | 2.37* | 2.37*   | 2.05* | 2.00*   |
| 6    | 1.00  | 0.99    | 0.99  | 0.98    | 1.00  | 0.99    | 1.00  | 0.99    | 1.00  | 0.99    |
| 7    | 0.20  | 0.19    | 0.19  | 0.18    | 0.20  | 0.19    | 0.20  | 0.19    | 0.20  | 0.19    |
| 8    | 0.20* | 0.19*   | 0.19* | 0.18*   | 0.20* | 0.19*   | 0.20* | 0.19*   | 0.20* | 0.19*   |
| 9    | 0.45  | 0.44    | 0.44  | 0.43    | 0.45  | 0.44    | 0.45  | 0.44    | 0.45  | 0.44    |
| 10   | 0.56  | 0.55    | 0.55  | 0.54    | 0.56  | 0.55    | 0.56  | 0.55    | 0.56  | 0.55    |
| 11   | 0.44  | 0.43    | 0.43  | 0.42    | 0.44  | 0.43    | 0.44  | 0.43    | 0.44  | 0.43    |
| 12   | 0.27  | 0.26    | 0.26  | 0.25    | 0.27  | 0.26    | 0.27  | 0.26    | 0.27  | 0.26    |
| 13   | 0.72  | 0.71    | 0.71  | 0.70    | 0.72  | 0.71    | 0.72  | 0.71    | 0.72  | 0.71    |
| 14   | 1.27  | 1.26    | 1.26  | 1.25    | 1.27  | 1.26    | 1.27  | 1.26    | 1.27  | 1.26    |
| 15   | 0.70  | 0.69    | 0.69  | 0.68    | 0.70  | 0.69    | 0.70  | 0.69    | 0.70  | 0.69    |
| 16   | 0.63  | 0.62    | 0.62  | 0.61    | 0.63  | 0.62    | 0.63  | 0.62    | 0.63  | 0.62    |
| 17   | 0.38  | 0.37    | 0.37  | 0.36    | 0.38  | 0.37    | 0.38  | 0.37    | 0.38  | 0.37    |
| 18   | 1.06  | 1.05    | 1.05  | 1.04    | 1.06  | 1.05    | 1.06  | 1.05    | 1.06  | 1.05    |

MMK values in bold represents presence of autocorrelation in rainfall series. Negative/positive Z value indicates decreasing/increasing trend. Shaded cells show that a grid has more than 2 series showing 10% changes.

* Represents significant trend.
Table 5
Result of MK (MMK) test (at 5% level) and percentage over 1949–2012 with autocorrelation.

| Grids | Seasonal | Mean MK (MMK) | Sen's slope | % change |
|-------|----------|---------------|-------------|----------|
|       | Annual   |               |             |          |
|       | Pre-Monsoon |            |             |          |
|       | Monsoon |       |             |          |
|       | Post-Monsoon |         |             |          |
|       | Winter |       |             |          |
|       | Annual   |               |             |          |
|       | Post-Monsoon |         |             |          |
|       | Pre-Monsoon |       |             |          |
|       | Winter |       |             |          |

Table 6
Results of homogeneity of trends between grid points on annual and seasonal basis.

Table 7
Results of MK (MMK) test statistic, Theil and Sen's slope and % change over Wainganga basin from.

4.8. Trend analysis of mean rainfall data over entire Wainganga basin

Mean rainfall series of annual rainfall data and seasonal rainfall data using all grids’ data were prepared for three time periods during 1901–2012, 1901–1948 and 1949–2012. The result of mean, autocorrelation, Z statistics of Mann–Kendall (MMK) test, Sen’s slope estimator test and % change for annual and seasonal rainfall series are given in Table 7(a–c). There is statistically non-significant decreasing trend found in annual and seasonal series in the entire basin during 1901–2012. There is statistically non-significant increasing trend in annual and seasonal rainfall over

5. Conclusions

In the present study, trend and homogeneity of trends for annual and seasonal rainfall series was analysed for Wainganga basin during the period 1901–2012 using CRU 0.5 × 0.5° gridded rainfall data. From the study, it is concluded that annual and monsoon rainfall is decreased in the Wainganga basin during the period 1901–2012. The most probable year of change in the basin is 1948. There is an increasing trend in the basin during the period 1901–1948, which got reversed during the period 1949–2012.
resulting in an overall decreasing trend in the basin. There is an overall decrease (−8.45%) in annual rainfall in the basin during the period 1901–2012. It is also found that the trends are homogeneous in the entire basin. Overall, the results of this study are in agreement with other studies conducted by many researchers in central India (Duhan and Pandey, 2013; Kumar and Jain, 2011; Singh et al., 2005).

Global climate shift (Baines, 2006) or weakening global monsoon circulation (Pant, 2003), reduction in forest cover (Nair et al., 2003; Ray et al., 2003, 2006) and increasing aerosol due to anthropogenic activities (Ackerman et al., 2000; Ramanathan et al., 2001, 2005; Sarkar and Kafatos, 2004) may be the probable causes of change in activities (Ackerman et al., 2000; Ramanathan et al., 2001, 2005; Ray et al., 2003, 2006) and increasing aerosol due to anthropogenic activities (Ackerman et al., 2000; Ramanathan et al., 2001, 2005; Sarkar and Kafatos, 2004) may be the probable causes of change in rainfall which were reported by Basistha et al. (2009).

Appendix A. Student’s ‘t’ test for autocorrelation

The presence of positive or negative autocorrelation affects the detection of trend in a series (Anderson, 1941; Hamed and Rao, 1998; Yue et al., 2002b). Serial independence is tested using

\[ t = \rho_1 \sqrt{\frac{n-2}{1-\rho_1^2}} \]

where, the test statistic \( t \) has a Student’s \( t \) distribution with \((n–2)\) degrees of freedom. If \( |t| > t_{\alpha/2} \), the null hypothesis about serial independence is rejected at significance level \( \alpha \).

Appendix B. Trend detection

Mann–Kendall test (MK)

MK test is the rank based nonparametric test and recently used by several researchers to detect trends in rainfall data (Mann, 1945; Kendall 1975; de la Casa and Nasello, 2010, 2012; Krishnakumar et al., 2009; Shifteh Somee et al., 2012; Subash et al., 2011; Tabari et al., 2011).

Test statistic \( S \) defined as:

\[ S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i) \]

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

\[ \text{sgn}(y) = \begin{cases} 1 & \text{if } (y > 0) \\ 0 & \text{if } (y = 0) \\ -1 & \text{if } (y < 0) \end{cases} \]

It has been documented that when \( n \geq 8 \), the statistic \( S \) is approximately normally distributed with the mean \( E(S) = 0 \) and variance as

\[ V(S) = \frac{n(n-1)(2n+5)}{18} - \frac{m}{18} \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5) \]

where, \( m \) is the number of tied groups and \( t_i \) is the size of the \( i \)th tied group. The standardised test statistic \( Z \) is computed by

\[ Z_{MK} = \begin{cases} \frac{S - 1}{\sqrt{V(S)}} & \text{when } S > 0 \\ 0 & \text{when } S = 0 \\ \frac{S + 1}{\sqrt{V(S)}} & \text{when } S < 0 \end{cases} \]

Modified Mann–Kendall test (MMK)

Pre-whitening has been used to detect a trend in a time series in presence of autocorrelation (Cunderlik and Burn, 2004). However, pre-whitening is reported to reduce the detection rate of significant trend in the MK test (Yue et al., 2003). Therefore, the MMK test (Hamed and Rao, 1998; Rao et al., 2003) has been employed for trend detection of an autocorrelated series. In this, the autocorrelation between ranks of the observations \( pk \) are evaluated after subtracting a non-parametric trend estimate such as Theil and Sen’s median slope from the data.

Only significant values of \( \rho_k \) are used to calculate variance correction factor \( n/n^2 \), as the variance of \( S \) is underestimated when data are positively auto-correlated:

\[ n/n^2 = 1 + \frac{2}{n(n-1)(n-2)} - \frac{n-1}{n-2} \sum_{k=1}^{n-1} (n-k)(n-k-1)(n-k-2)/n \]

where, \( n \) is actual number of observations, \( n^2 \) is considered as an ‘effective’ number of observations to account for autocorrelation in data and \( \rho_k \) is the autocorrelation function of ranks of the observations.

The corrected variance is then computed as

\[ V^*(S) = V(S) \times \frac{n}{n^2} \]

where,

\[ V(S) = \frac{n(n-1)(2n+5) - m}{18} \sum_{i=1}^{m} t_i(t_i-1)(2t_i+5) \]

The standardized test statistic \( Z(N(0,1)) \) is computed by

\[ Z_{MK} = \begin{cases} \frac{S - 1}{\sqrt{V(S)}} & \text{when } S > 0 \\ 0 & \text{when } S = 0 \\ \frac{S + 1}{\sqrt{V(S)}} & \text{when } S < 0 \end{cases} \]

where,

\[ S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i) \]

Appendix C. Trend slope

Theil and Sen’s median slope

The slope of \( n \) pairs of data points was estimated using the Theil–Sen’s estimator (Theil, 1950; Sen, 1968) is calculated as

\[ Q_i = (x_j - x_k)/(j-k) \quad \text{for } i = 1, \ldots, N \]

where, \( x_j \) and \( x_k \) are data values at times \( j \) and \( k \) (\( j > k \)) respectively. The median of these \( N \) values of \( Q_i \) is Sen’s estimator of slope. If there is only one data in each time period, then

\[ N = n(n-1)/2 \]

where \( n \) is the number of time periods. The median of the \( N \) estimated slopes is obtained in the usual way, i.e., the \( N \) values of \( Q_i \) are ranked by \( Q_1 \leq Q_2 \leq \cdots \leq Q_{N-1} \leq Q_N \) and

\[ \text{Sen’s estimator} = \begin{cases} Q_{N+1}/2 & \text{if } N \text{ is odd} \\ (1/2)(Q_{N/2} + Q_{N/2+1})/2 & \text{if } N \text{ is even} \end{cases} \]

Appendix D. Change magnitude as percentage of mean

Change percentage has been computed by approximating it with a linear trend. That is change percentage equals median slope multiplied by the period length divided by the corresponding mean, expressed as percentage (Pc) followed by
Appendix E. Test for jump/shift detection

Pettitt–Mann–Whitney test (PMW) (Pettitt, 1979)

Let $T$ be the length of the time series and let $t$ be the year of the most likely change point. The single time series is considered as two samples represented by $X_1, X_2, \ldots, X_T$.

The index is:

$$ V_t = \sum_{j=1}^{T} \text{sgn}(X_t - X_j) $$

where,

$$ \text{sgn}(x) = \begin{cases} 
1 & \text{for } x > 0 \\
0 & \text{for } x = 0 \\
-1 & \text{for } x < 0 
\end{cases} $$

Let a further index $U_t$ be defined as

$$ U_t = \sum_{i=1}^{T} \sum_{j=1}^{T} \text{sgn}(X_i - X_j) $$

The most significant change point $t$ can be identified as the point where the value of $|U_t|$ is maximum:

$$ K_T = \max_{1 \leq t \leq T} |U_t| $$

The probability of a change point being at the year where $|U_t|$ is the maximum, is approximated by

$$ p = 1 - \exp \left( -\frac{6K_T^2}{T^3 + T^2} \right) $$

If further, it is introduced, for $1 \leq t \leq T$, the series

$$ U(t) = |U_t| $$

and it is defined

$$ P(t) = 1 - \exp \left( -\frac{6U(t)^2}{T^3 + T^2} \right) $$

a series of probabilities of significance for each year can be obtained.

Appendix F. Test for homogeneity

van Belle and Hughes’ homogeneity of trend test

Homogeneity test (van Belle and Hughes, 1984; Helsel and Hirsch, 2002) is used on data by combining data from several stationsto obtain a single global trend. The method uses the Mann–Kendall-statistic for each station. To test for homogeneity of trend direction at multiple stations the homogeneity $\chi^2$ statistic $\chi^2_{\text{homog}}$ is calculated as:

$$ \chi^2_{\text{homog}} = \chi^2_{\text{total}} - \chi^2_{\text{trend}} = \sum_{j=1}^{p} Z_j^2 - pZ^2 $$

where $p$ is the total number of stations; $Z_j$ is the test statistic $Z_j$ for the $j$th station obtained as:

$$ Z = \frac{1}{p} \sum_{i=1}^{p} Z_j $$

Pettitt’s test

The Pettitt’s test is a nonparametric test that requires no assumption about the distribution of data. The Pettitt’s test is an adaptation of the tank-based Mann–Whitney test that allows identifying the time at which the shift occurs.

We reformulate the null and alternative hypotheses:

H0. The $T$ variables follow one or more distributions that have the same location parameter.

Two-tailed test: $H_a$: There exists a time $t$ from which the variables change of location parameter.

Left-tailed test: $H_a$: There exists a time $t$ from which the variables location is reduced by $D$.

Left-tailed test: $H_a$: There exists a time $t$ from which the variables location is augmented by $D$.

The statistic used for the Pettitt’s test is computed as follows:

$$ U_{t,T} = \sum_{i=1}^{T} \sum_{j=1}^{T} D_{ij} $$

The Pettitt’s statistic for the various alternative hypotheses is given by:

$$ K_T = \max_{1 \leq t \leq T} |U_{t,T}| $$

for the two —tailed case

$$ K_T = -\max_{1 \leq t \leq T} U_{t,T} $$

for the left —tailed case

$$ K_T = \max_{1 \leq t \leq T} U_{t,T,T} $$

for the right —tailed case

Alexandersson’s SNHT test

The SNHT test (Standard Normal Homogeneity Test) was developed by Alexandersson (1986), Alexandersson and Moberg (1997) to detect a change in a series of rainfall data. The test is applied to a series of ratios that compare the observations of a measuring station with the average of several stations. The ratios are then standardized. The series of $X_i$ corresponds here to the standardized ratios. The null and alternative hypotheses are determined by:

H0. The $T$ variables $X_i$ follow an $N(0,1)$ distribution.

Ha: Between times 1 and $n$ the variables follow an $N(\mu 1, 1)$ distribution, and between $n + 1$ and $T$ they follow an $N(\mu 2, 1)$ distribution.

The Petitt statistic is defined by:

$$ T_0 = \max_{1 \leq t \leq T} \left( |vz_1^2 + (n - vz_2^2) | \right) $$

with

$$ z_1 = \frac{1}{v} \sum_{i=1}^{v} x_i $$

$$ z_2 = \frac{1}{n-v} \sum_{i=v+1}^{T} x_i $$

The $T_0$ statistic derives from a calculation comparing the likelihood of the two alternative models. The model corresponding to Ha implies that $11 \text{ and } 12$ are estimated while determining the $n$ parameter maximising the likelihood.
**Buishand's test**

The **Buishand's test** (1982) can be used on variables following any type of distribution, but its properties have been particularly studied for the normal case. In his article, Buishand focuses on the case of the two-tailed test, but for the Q statistic presented below the one-sided cases are also possible. Buishand has developed a second statistic \( R \), for which only a bilateral hypothesis is possible.

In the case of the Q statistic, the null and alternative hypotheses are given by:

**H0.** The \( T \) variables follow one or more distributions that have the same mean.

Two-tailed test: Ha: There exists a time \( t \) from which the variables change of mean. 
Left-tailed test: Ha: There exists a time \( t \) from which the variables mean is reduced by \( \Delta \).
Left-tailed test: Ha: There exists a time \( t \) from which the variables mean is augmented by \( \Delta \).

We define

\[
S_0^* = 0, \quad S_t^* = z_t = \sum_{i=1}^{k} (x_i - \mu), \quad k, 1, 2, \ldots, T
\]

and

\[
S_k^{**} = S_k^*/\sigma
\]

The Buishand’s Q statistics are computed as follows:

\[
Q = \max_{1 \leq t \leq T} (S_t^{**}), \text{ for the two -- tailed case}
\]

\[
Q^- = \min_{1 \leq t \leq T} (S_t^{**}), \quad \text{for the left -- tailed case}
\]

the null and alternative hypotheses are given by:

**H0.** The \( T \) variables follow one or more distributions that have the same mean.

Two-sided test: Ha: The \( T \) variables are not homogeneous for what concerns their mean.

The Buishand’s \( R \) statistic is computed as:

\[
R = \max_{1 \leq t \leq T} (S_t^{**}) - \min_{1 \leq t \leq T} (S_t^{**})
\]

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