Pan evaporative changes in transboundary Godavari River basin, India

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Abstract
Pan evaporative changes are one of the key components of water resources management of a river basin under changing climate and anthropogenic-induced warming. The present study was undertaken for transboundary Godavari River basin (India) to identify the trends in pan evaporation (E\textsubscript{pan}) by non-parametric Mann–Kendall (MK) test in annual, seasonal and monthly time scales. The Pettitt test, a non-parametric test, was also used in this study to detect abrupt changes in the mean of the distribution of the \(E_{\text{pan}}\) in the Godavari basin. Furthermore, the stepwise regression analysis was performed to find out the cause of the observed \(E_{\text{pan}}\) changes in the basin. On seasonal (monthly) time scales, statistically significant decreasing trends in \(E_{\text{pan}}\) were witnessed in the pre-monsoon season (in the months of March, April and May) in all the seven sites of the Godavari River basin. On the other hand, four sites witnessed statistically significant increasing trends in minimum temperature (maximum temperature) in the month of July (December) and in the monsoon (post-monsoon) season in the Godavari River basin. Statistically significant decreasing (increasing) trends in wind speed (relative humidity) in the pre-monsoon season and in the month of March at these seven sites support the observed decline in the evaporative demand in the basin leading to possible enhancement in the total yield of the Godavari River basin. Results of stepwise regression analysis showed that wind speed followed by relative humidity was found to be two main causative parameters of the observed decline in the \(E_{\text{pan}}\) under the warmer environments in the Godavari River basin. Pettitt’s test shows year 1991–1992 to be the probable year of change in the \(E_{\text{pan}}\) in the Godavari River basin.

1 Introduction
Evaporation, one of the main components of the hydrologic cycle, plays a vital role in agricultural and hydro-meteorological studies, water resources management and irrigation scheduling (Gundekar et al. 2008). Evaporation is influenced by a large number of meteorological factors, such as, air temperature, relative humidity, sunshine duration and wind speed. Evaporation is a complex process which is governed by several atmospheric parameters (Rayner 2007; Yan et al. 2019). Changes in air temperature can modify the saturation vapour pressure, which in turn may alter the evaporation rate (Dinpashoh et al. 2011).

The global air temperature has increased by 0.6 °C in the last century due to anthropogenic factors, such as, population growth, deforestation, changes in land use and increase in atmospheric concentrations of greenhouse gases (Ganguly and Iyer 2009; Jhajharia and Singh 2011). Several studies have been carried out over different parts of India for analysis of trends in various climatic parameters. Shivam et al. (2017) analysed the trends in rainfall events over a river basin of north-eastern India and reported significant rising trend in annual rainfall along with increase in extreme rainfall events. Goyal (2014) studied the trends and change point analysis in long-term rainfall data of the state of Assam, India and found 1959 as a probable year of change in the rainfall pattern. Jaiswal et al. (2014) reported the falling trends of \(E_{\text{pan}}\) in spite of significant rising trends in annual minimum, maximum temperatures and relative humidity attributed mainly to strong stilling phenomenon along with solar dimming in the district of Raipur, Chhattisgarh state (India). Krishan et al. (2017) analysed trends in rainfall and dry/wet years over a canal command area of Northern India and reported significant decreasing trends in annual and monsoon rainfall. Hadi and Tombul (2018) reported statistically significant increasing trend in temperature by using...
the Mann–Kendall test at the rate of 0.88 °C/century and no trends in precipitation over Turkey.

Mondal et al. (2015) reported decreasing trends in the monsoon and annual rainfall in most of the sub-divisions of India. Jhajharia (2012) reported a rise in air temperature over a southern peninsular river basin of India using the temperature data of 35 sites located in different sub-basins of the Godavari River, which has implications on increased evaporation rate affecting the water availability in the basin. Chakraborty et al. (2017) studied the change point detection in mean air temperature in Northeast India and found a significant rising trend in average temperature with change point in the 1990s at most of the north-eastern stations. Several studies have been carried out for the trend analysis of meteorological parameters, such as, temperature and precipitation for Indian rivers. However, there have been very fewer studies available in the literature pertaining to the identification of trends in evaporation and evapotranspiration, which plays a very important role in the water availability in a river basin. Goroshi et al. (2017) carried out trend analysis of evapotranspiration over the Indian subcontinent and reported a strong decreasing trend in the forest region contrary to the rising trends in the arid and semi-arid regions. Evaporation process plays an important role in assessment of the surface water availability in a region. The higher evaporation rate as compared to the rainfall causes surface water deficit in a region, which can also be monitored by the drought analysis (Amrit et al. 2019).

Several studies on the identification of trends in temperature and precipitation and drought analysis (Mishra et al. 2019) have been carried out for the Godavari River basin, but there is no study on evaporation trends and change point analysis. Thus, the Godavari River is selected with the objective of studying trends in pan evaporation (E_p) through the Mann–Kendall (MK) test in annual, seasonal and monthly time scales. The objectives of the study are as follows: (i) to identify the trends in E_p over the historical observed period in the Godavari River basin by using the Mann–Kendall (MK) test; (ii) to detect abrupt changes in the mean of the distribution of the E_p in the basin by using the Pettitt test and (iii) to find out the cause of the observed E_p changes in the Godavari River basin.

2 Study area and data

2.1 Details of study area

The Godavari River is the largest river of peninsular India and is held in reverence as “Dakshin Ganga” (Ganges of South). Several holy places are located on the banks of the river at Nasik and Bhadrachalam in the Godavari basin. The river basin (longitudes 73° 26’ and 83° 07’ E; latitudes 16° 16’ and 23° 43’ N) rises in Sahyadris about 80 km from the Arabian Sea at Trimbakeshwar in Nasik district of Maharashtra (Jain et al. 2007). The basin extends over about 9.5% of the total geographical area of India. The Godavari River passes through seven states, namely, Maharashtra, Telangana, Madhya Pradesh (MP), Karnataka, Chhattisgarh, Orissa and Andhra Pradesh (AP) before merging in the Bay of Bengal. It is worth to mention that two new states were created in the Godavari basin since 2000. On 1 November 2000, the state of Chhattisgarh was created by bifurcating the erstwhile state of MP, the largest Indian state before the bifurcation. The state of Telangana was created by dividing the erstwhile state of AP on 2 June 2014. The creation of the two new co-basin states in the Godavari River basin may create water-sharing problems amongst the other co-basin states in near future under the warmer environments in the basin leading to unusually high water demands due to rise in population and increase in living standards of the people (Jhajharia 2012).

Godavari River is purely rainfed and its main tributaries include Pravara, Purna, Manjra, Maner, Penganga, Pranhita, Indravati, Sabari, etc. The river carries enormous quantities of water during monsoon. The basin consists of large undulating plains separated by low flat topped hill ranges and the main soil types found are black soils, red soils, lateritic soils, alluvium, saline and alkaline soils (CWC 1987, 1999). The average annual rainfall of the basin is about 1132 mm, and the mean surface temperature ranges from 14.5 to 35.5 °C in different parts of the Godavari River basin (Jhajharia et al. 2014).

2.2 Data

The monthly data of E_p were obtained from the India Meteorological Department (IMD), Pune (Maharashtra), for different periods, especially from 1969 to 2007, at seven stations, namely, Aurangabad, Betul, Hyderabad, Jagdalpur, Nagpur, Yeotmal and Ramagundam located in different sub-basins of the Godavari River. The details and location of the selected sites are given in Table 1 and Fig. 1, respectively. The monthly dataset were used to obtain the annual and seasonal values of E_p for these sites of the basin. The monthly and annual average data of total E_p of all the stations of the basin are given in Table 2. The total average annual E_p values vary in the range of 1400.80 to 2129.70 mm in the Godavari River basin.

3 Methodology

3.1 Trend analysis

In the present study, the MK test was used for detecting trends in E_p and other climatic parameters as non-parametric MK test is more suitable for non-normally distributed and censored data with missing values, and are less influenced by the presence of outliers in the data (Jhajharia et al. 2009; Chattopadhyay et al. 2011). Zhang et al. (2001) have reported that if there is persistence in the time series, then the non-parametric test will
suggest significant trend in the series. Thus, the effect of serial dependence sometimes creates problem in testing and interpretation of trends. In the beginning, we tested the significance of lag-1 serial correlation (r1) for the $E_{\text{pan}}$ time series to eliminate the effect of serial correlation in this paper. If the absolute value of r1 was found to be less than the significance level value, then the Mann–Kendall (MK) test was used for identifying trends in $E_{\text{pan}}$ and other time series. Otherwise, the effect of serial correlation was removed from the time series by pre-whitening prior to applying the MK test. Further, details about the pre-whitening might be referred in Kumar et al. (2009), Partal and Kahya (2006), Dinpashoh et al. (2011), Jhajharia et al. (2012a, b, 2014), Zamani et al. (2017), Ahmadi et al. (2018) and Mirabbasi et al. (2020). The MK test (Mann, 1945; Kendall, 1975) was carried out by calculating the values of the S and the Z statistic, as described in the Eqs. 1 and 2, respectively.

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

where \( n \) is the number of observations, \( x_j \) is the \( j \)th observation and \( \text{sgn} \) (.) is the sign function computed as under the assumption that the data are independent and identically distributed.

\[ \text{var}(s) = \frac{1}{18} \left[ n(n-1)(2n+5) - \sum f_i(f_i-1)(2f_i+5) \right] \]

where var(s) is the variance of the series s and \( f_i \) is the number of tied group in given time series.

Further, the MK statistic (Z) can be computed as follows:

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**Table 1** Details of sites located in the Godavari River basin

| S. no | Name of site | Code of site | State | Lat. (N) | Long. (E) | Elev., m amsl |
|-------|-------------|--------------|-------|---------|-----------|---------------|
| 1     | Aurangabad  | 43,014       | MAH   | 19° 51' | 75° 24'  | 579.0         |
| 2     | Betul       | 42,860       | MP    | 21° 52' | 77° 56'  | 658.0         |
| 3     | Hyderabad   | 43,128       | AP    | 17° 27' | 78° 28'  | 489.0         |
| 4     | Jagdalpur   | 43,041       | CHH   | 19° 05' | 82° 02'  | 554.0         |
| 5     | Nagpur      | 42,867       | MAH   | 21° 06' | 79° 03'  | 310.0         |
| 6     | Yeotmal     | 43,017       | MAH   | 19° 16' | 76° 50'  | 423.0         |
| 7     | Ramagundam  | 43,086       | AP    | 18° 46' | 79° 26'  | 179.0         |

Note: Lat, long, elev, m amsl, N, MAH, AP, MP, KAR and CHH denote latitude, longitude, elevation, metre above mean sea level, north, Maharashtra, Andhra Pradesh, Madhya Pradesh, Karnataka and Chhattisgarh, respectively.
Tables

**Table 2** Mean total pan evaporation over Godavari River basin

| Time scale | Aurangabad | Betul | Hyderabad | Jagdalpur | Nagpur | Yeotmal | Ramgundam | Basin |
|------------|------------|-------|-----------|-----------|--------|---------|-----------|-------|
| January    | 121.0      | 95.1  | 142.1     | 87.4      | 108.3  | 152.8   | 91.2      | 113.9 |
| February   | 146.7      | 100.6 | 164.6     | 113.3     | 126.2  | 183.7   | 121.5     | 136.7 |
| March      | 219.1      | 127.3 | 228.3     | 169.4     | 184.6  | 273.6   | 181.4     | 197.8 |
| April      | 273.8      | 150.4 | 249.5     | 194.1     | 227.3  | 346.2   | 225.2     | 238.0 |
| May        | 310.8      | 188.0 | 280.6     | 207.2     | 270.4  | 419.3   | 275.2     | 278.8 |
| June       | 194.4      | 143.1 | 198.4     | 148.5     | 190.8  | 265.1   | 191.0     | 190.2 |
| July       | 131.5      | 102.1 | 162.6     | 104.4     | 120.1  | 176.1   | 120.0     | 130.9 |
| August     | 108.6      | 87.8  | 144.3     | 89.1      | 106.5  | 149.9   | 102.9     | 112.8 |
| September  | 123.9      | 100.1 | 147.3     | 100.3     | 125.3  | 158.9   | 105.1     | 122.8 |
| October    | 148.8      | 113.2 | 152.4     | 104.8     | 134.6  | 177.5   | 106.6     | 134.0 |
| November   | 116.2      | 98.8  | 133.9     | 92.3      | 113.1  | 161.0   | 90.1      | 115.1 |
| December   | 115.2      | 94.3  | 125.7     | 79.9      | 102.1  | 142.4   | 84.3      | 106.4 |
| Annual     | 2010.0     | 1400.8| 2129.7    | 1490.8    | 1809.4 | 2606.4  | 1694.5    | 1877.4 |

**Table 3** Values obtained for pan evaporation over Godavari River basin

| Time scale       | Aurangabad | Betul | Hyderabad | Jagdalpur | Nagpur | Yeotmal | Ram       |
|------------------|------------|-------|-----------|-----------|--------|---------|-----------|
| January          | -4.4       | -1.5  | -4.8      | 0.4       | -1.3   | -1.2    | -2.3      |
| February         | -4.8       | -3.0  | -4.7      | -1.4      | -1.7   | -4.1    | -2.9      |
| March            | -5.2       | -4.3  | -5.8      | -3.0      | -3.9   | -3.8    | -4.3      |
| April            | -4.9       | -4.1  | -4.8      | -3.3      | -5.3   | -4.3    | -3.8      |
| May              | -4.7       | -5.1  | -4.1      | -2.7      | -5.0   | -2.9    | -3.8      |
| June             | -5.0       | -4.7  | -4.4      | -0.9      | -2.9   | -1.5    | -4.2      |
| July             | -4.2       | -3.1  | -3.9      | 0.5       | -2.7   | -2.7    | -3.4      |
| August           | -4.4       | -2.5  | -4.1      | 0.2       | -1.9   | -1.7    | -3.3      |
| September        | -3.5       | -2.6  | -4.4      | 0.3       | -1.8   | -2.1    | -2.5      |
| October          | -4.2       | -3.2  | -5.1      | 0.2       | -1.6   | -2.5    | -1.7      |
| November         | -3.6       | -2.4  | -4.2      | 0.5       | -2.2   | -2.8    | -2.3      |
| December         | -3.2       | -0.9  | -4.3      | 1.0       | -2.3   | -2.3    | -1.9      |
| Annual           | -5.4       | -4.0  | -5.9      | -1.5      | -4.3   | -5.0    | -4.3      |
| Winter           | -4.8       | -2.4  | -5.2      | -0.7      | -1.8   | -3.2    | -2.8      |
| Pre-monsoon      | -5.3       | -4.8  | -5.3      | -3.6      | -5.3   | -4.6    | -4.3      |
| Monsoon          | -5.2       | -3.7  | -5.5      | -0.5      | -3.2   | -3.4    | -3.9      |
| Post-monsoon     | -3.5       | -1.5  | -4.4      | 1.0       | -2.4   | -2.9    | -2.0      |

Note: Bold numbers are statistically significant at 5% level of significance. Ram denotes Ramgundam. Italics numbers are non-significant at 5% level of significance.

**3.2 Change point detection**

The Pettitt (1979) test is a non-parametric change detection test, which is used to find the probable year of change in the pattern of the recorded climatic time series. It detects change in the mean of a time series and the year when the change starts reflecting in the series. The non-parametric test statistics $U_t$ for this test may be described as follows:

$$U_t = \sum_{i=1}^{t} \sum_{j=t+1}^{n} \text{sign}(x_i - x_j)$$  \hspace{1cm} \text{(3)}$$

$$\text{sign}(x_i - x_j) = \begin{cases} 
1 & \text{if} \quad x_i > x_j \\
0 & \text{if} \quad x_i = x_j \\
-1 & \text{if} \quad x_i < x_j
\end{cases}$$  \hspace{1cm} \text{(4)}$$

The test statistic $K$ and the confidence level ($\rho$) for the sample length (n) may be described as following:

$$K = \max(U_t)$$  \hspace{1cm} \text{(5)}$$
When \( \rho \) is smaller than the specific confidence level, the null hypothesis is rejected. The approximate significance probability (p) for a change point is defined as given below:

\[
P = 1 - \rho
\]

4 Results and discussion

Trends in \( \text{E}_\text{pan} \) and other climatic variables, i.e. temperature, bright sunshine duration, wind speed and relative humidity were obtained through the Mann–Kendall test for different durations: annual; seasonal: winter, pre-monsoon, monsoon and post-monsoon; and monthly: January to December. The results are discussed as follows.

4.1 Analysis of temporal trends in \( \text{E}_\text{pan} \)

The records of \( \text{E}_\text{pan} \) are measured through the USWB Class A Pan Evaporimeter at seven sites located in different co-basin states of the Godavari River. The annual \( \text{E}_\text{pan} \) values varied from about 1401.0 to 2606.4 mm over the basin. The observed total \( \text{E}_\text{pan} \) in the Godavari basin as a whole is found to be about 1877.4 mm per annum. The average total \( \text{E}_\text{pan} \) during the winter season is in the range of around 106–114 mm over the whole basin. The mean monthly \( \text{E}_\text{pan} \) over the Godavari basin varies in the range of around 198–279 mm during the months of March to May in the pre-monsoon season. The monthly

\[
\rho = \exp \left[ -\frac{K}{n^2 + n^3} \right] 
\]

Fig. 2  Annual pan evaporation (mm) variation over the selected stations of Godavari basin
E$_{\text{pan}}$ attain the peak values in the month of May for most of the sites in the Godavari basin. Thereafter, the monthly E$_{\text{pan}}$ values decreased gradually during the monsoon season from the months of June and July, and reaching the lowest E$_{\text{pan}}$ values in August possibly due to very high relative humidity leaving little scope for water to evaporate from the surface to the surrounding air in the basin. However, afterwards, the monthly E$_{\text{pan}}$ values increased a little bit in September and October due to comparatively drier climate in these 2 months in the Godavari basin. On a seasonal time scale, the E$_{\text{pan}}$ values in the pre-monsoon season accounted for about 38.1% of the annual E$_{\text{pan}}$ in only 3 months. However, E$_{\text{pan}}$ values in the winter and post-monsoon seasons accounted for about 25.2% of the annual E$_{\text{pan}}$ during 4 months from November to February in the basin.

The trends in E$_{\text{pan}}$ at seven sites in monthly, annual and seasonal time scales were identified through the non-parametric MK test. Table 3 shows the Z statistics values obtained through the MK test for identifying trends in E$_{\text{pan}}$ over seven sites located in Godavari basin in different time scales. It can be inferred from Table 3 that all sites witnessed downward trends in the E$_{\text{pan}}$ in annual time scale. However, about 86% of the stations witnessed statistically significant decreasing trends at 1% level of significance in E$_{\text{pan}}$ in annual time scale. Figure 2 shows the E$_{\text{pan}}$ time series and the trend lines of different sites in the Godavari basin indicating downward trends in annual time scale. In annual time

![Fig. 3 Mean relative humidity (%) in variation over the Godavari basin](image-url)
scale, statistically significant decreasing trends in total $E_{\text{pan}}$ were witnessed in the range of $(−) 18.1$ to $(−) 48.0$ mm/annum. On seasonal time scale, the $E_{\text{pan}}$ trends results were almost similar to annual time scale, i.e. all the sites located in the basin witnessed decreasing trends in winter, pre-monsoon and monsoon seasons. However, at least six sites (five sites each) witnessed statistically significant decreasing trends in $E_{\text{pan}}$ at 1% level of significance in pre-monsoon and monsoon (winter and post-monsoon) seasons over Godavari (see Table 3). Results indicate the presence of seasonality in the $E_{\text{pan}}$ data in the basin as the strongest $E_{\text{pan}}$ decreases are observed in the pre-monsoon season in comparison to the trends observed in winter and post-monsoon seasons.

On monthly time scale, all the sites observed comparatively stronger $E_{\text{pan}}$ decreases at 1% level of significance during the months of March to May (months comprising the pre-monsoon season) in the Godavari basin. Similarly, all but one station observed statistically significant downward trends in the $E_{\text{pan}}$ during the months of June, July and November in the Godavari basin. On the other hand, half of the sites witnessed no trends in the $E_{\text{pan}}$ during the months of December and January in the basin. It is worth to mention that only Jagdalpur site observed increasing trends in $E_{\text{pan}}$, although statistically non-significant, during the months of July to December and January (months comprising the monsoon and post-monsoon seasons).

### 4.2 Analysis of temporal trends in other climatic parameters

#### 4.2.1 Trends in relative humidity and temperature

The data of the morning relative humidity ($RH_{\text{max}}$) and the afternoon RH ($RH_{\text{min}}$) are usually recorded at 8.30 and at 17.30 h Indian standard time (IST), respectively, at seven IMD meteorological observatories maintained in the basin. The mean RH, i.e. $RH_{\text{mean}}$, data were obtained by taking the average of the morning and afternoon values of RH of a given site for any time scale. The annual $RH_{\text{mean}}$ is found to be ranging from 40 to 70% in the Godavari River basin. Figure 3 shows the time series of $RH_{\text{mean}}$ and trend lines indicating upward trends on annual time scale over different stations in the Godavari basin. Table 4 shows the values of the Z statistic obtained through the MK test for identifying trends in $RH_{\text{mean}}$ over seven sites located in Godavari basin in different time scales. Out of the selected seven sites, five sites (one station, Hyderabad) witnessed upward trends in $RH_{\text{mean}}$ at 5% (at 10%) level of significance in annual time scale. Thus, statistically significant increases in the $RH_{\text{mean}}$ were observed in the range of 5 (Hyderabad) to 25% (Aurangabad) per 100 years in annual time scale in the Godavari River basin.

On seasonal time scale, $RH_{\text{mean}}$ trends are almost similar to $RH_{\text{mean}}$ trends observed in annual time scale, i.e. seven (five) sites located in the Godavari River basin witnessed statistically significant increasing trends at 5% level of significance in $RH_{\text{mean}}$ in pre-monsoon season (winter, monsoon

### Table 4 Z values obtained for mean relative humidity over Godavari River basin

| Time scale   | Aurangabad | Betul | Hyderabad | Jagdalpur | Nagpur | Yeotmal | Ram |
|--------------|------------|-------|-----------|-----------|--------|---------|-----|
| January      | 3.6        | 3.5   | 0.2       | 2.7       | 1.8*   | 0.5     | 4.0 |
| February     | 3.6        | 3.8   | 0.7       | 1.9*      | 1.7*   | 1.3     | 3.4 |
| March        | 2.5        | 3.4   | 2.0       | 3.7       | 1.7*   | 2.0     | 4.3 |
| April        | 2.9        | 3.7   | 1.0       | 1.3       | 1.5    | 2.4     | 2.4 |
| May          | 2.8        | 2.2   | 1.2       | 2.5       | 1.8*   | 0.8     | 1.9*|
| June         | 3.4        | 1.1   | 1.0       | 1.9*      | 0.6    | −0.9    | 2.2 |
| July         | 2.6        | 0.2   | 0.0       | 2.2       | 1.3    | 0.3     | 1.9*|
| August       | 3.8        | 1.9*  | 2.1       | 2.6       | 2.0    | −0.7    | 2.6 |
| September    | 2.8        | 0.7   | 0.0       | 1.7*      | 1.4    | 0.3     | 1.7*|
| October      | 3.6        | 3.1   | 0.5       | 2.4       | 3.5    | 1.7*    | 2.7 |
| November     | 2.4        | 2.9   | −0.3      | 2.6       | 3.5    | 2.1     | 2.7 |
| December     | 2.6        | 1.4   | −1.2      | 2.2       | 1.5    | 0.2     | 3.0 |
| Annual       | 4.7        | 4.5   | 1.9*      | 4.4       | 3.7    | 2.3     | 4.6 |
| Winter       | 4.0        | 3.8   | 0.8       | 2.9       | 2.1    | 1.2     | 4.2 |
| Pre-monsoon  | 3.4        | 4.1   | 2.3       | 2.8       | 2.1    | 2.6     | 4.2 |
| Monsoon      | 4.6        | 2.3   | 1.5       | 3.3       | 2.5    | 0.1     | 3.4 |
| Post-monsoon | 2.7        | 2.8   | −1.2      | 2.6       | 2.2    | 1.4     | 3.2 |

Note: Bold number (italic number *) is statistically significant at 5% (10%) level of significance. Ram denotes Ramagundam. Italics numbers are non-significant at 10% level of significance.
and post-monsoon seasons). On monthly time scale, mostly upward trends in RH$_{\text{mean}}$ were witnessed over almost all the sites from January to December (see Table 4). Five sites witnessed increasing trends in RH$_{\text{mean}}$ in all the 12 months. Similarly, seven (six) sites witnessed statistically significant increasing trends in RH$_{\text{mean}}$ in the month of March (in the months of August, October and November). However, three stations each witnessed statistically significant increasing trends in RH$_{\text{mean}}$ in annual and seasonal time scales support the significant decreases in pan evaporation, i.e. increase in moisture in the air may decrease the evaporative demand of the atmosphere in these time scales in the Godavari River basin. Further, the increasing trends in relative humidity may lead to surface warming because of more heat trapping caused by the increase in water vapour in the atmosphere over the Godavari River basin.

The trends in maximum (day) and minimum (night) temperatures in monthly, annual and seasonal time scales were also identified through the non-parametric MK test. Tables 5, 6 and 7 show the values of the Z statistic obtained through the MK test for identifying trends in day and night temperatures in different time scales in the Godavari basin. One site, namely, Yeotmal witnessed statistically significant cooling trends at 5% level of significance in night temperature (day temperature) in winter season and January, September and December (in annual duration, post-monsoon season and in the month of October) in the basin. On the other hand, five sites each and four sites each witnessed statistically significant increasing trends in night temperature in July and September, and in annual time scale and in monsoon season. Similarly, four sites (three sites) each witnessed statistically significant increasing trends in day temperature in December, annual time scale and post-monsoon season (January, September and November) in the basin. Day temperature remained trendless during the months of February to August in the basin. However, night temperature remained trendless in June and August in the Godavari basin.

### 4.2.2 Trends in wind speed and sunshine duration

Table 8 shows the values of the Z statistic obtained through the MK test for identifying trends in wind speed for the seven sites located in the Godavari basin in monthly, annual and seasonal time scales. The wind speed data were measured by the cup-anemometer installed at height of 2.0 m above the ground level. All the sites witnessed strong wind speed decreases, mostly at 1% level of significance, in annual and seasonal time scales in the basin. Similar strong wind speed decreases are observed in the basin at all the sites in almost all the 12 months as most of the trends are

### Table 5: Z values obtained for minimum temperature over sites of Godavari River basin

| S. no | Name of site | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|-------|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1     | Aurangabad   | 3.64| 3.95| 3.88| 2.92| 4.73| 3.84| 4.37| 4.28| 4.77| 2.82| 1.84 | 1.44|
| 2     | Betul        | 0.53| 0.44| –0.49| 0.48| 2.71| 1.67| 2.10| 1.26| 1.66 | 1.40| 0.81 | –0.64|
| 3     | Hyderabad    | 2.45| 3.01| 2.55| 1.78 | 2.09| 1.48| 1.45| 0.73 | 3.22 | 2.76 | 2.48 | 0.51|
| 4     | Jagdalpur    | –0.88| –1.39| –1.36| –0.22 | –0.58| 0.72 | 2.25| 1.54| 1.69 | 0.46 | –0.20 | –1.39|
| 5     | Nagpur       | 1.54| 2.89| 2.26| 0.55 | 0.23 | 0.81 | 2.72| 0.85 | 2.05 | 1.86 | 1.36 | 1.10|
| 6     | Yeotmal      | –1.98| –1.46| –1.08| –1.85 | –1.40| 0.16 | –0.20| –0.29 | –2.16 | 0.07 | –0.26 | –2.08|
| 7     | Ramagundam   | –0.65| –0.78| –1.60| –1.29 | –0.85| 0.03 | 1.73 | 0.66 | 0.93 | –0.44 | –0.82 | –1.67|

Note: Bold numbers (bold numbers*) are statistically significant at 5% (10%) level of significance.

### Table 6: Z values obtained for maximum temperature over sites of Godavari River basin

| S. no | Name of site | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|-------|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1     | Aurangabad   | 1.18| 0.05| 0.54| 0.87 | 0.02| –0.58| –1.14| –2.09 | –0.55| –1.08| 0.93 | 1.54|
| 2     | Betul        | 2.36| 1.20| 1.37| 2.65 | 2.48| 0.75 | 0.55 | 0.64 | 3.07 | 1.80 | 2.29 | 3.62|
| 3     | Hyderabad    | 2.40| 0.83| 1.75 | 1.09 | 1.62| –0.63| 1.60 | 0.09 | 2.28 | 0.92 | 2.32 | 2.09|
| 4     | Jagdalpur    | 1.92 | 0.58| 0.43| 0.61 | –0.46 | 0.09 | 1.89 | 0.16 | 2.69 | 2.93 | 2.11 | 3.09|
| 5     | Nagpur       | 0.73 | –0.36| –0.08| 0.82 | 1.42 | 0.53 | –0.21 | 0.38 | 1.18 | 0.36 | 1.61 | 3.18|
| 6     | Yeotmal      | –0.52| –1.28| –0.03| –0.46 | –1.60 | 0.13 | –1.14| –0.26 | –1.43 | –1.98 | –1.04 | –1.53|
| 7     | Ramagundam   | –0.49| –1.19| –0.54| –0.43| 0.17 | –1.52 | –0.18 | –1.64 | 0.91 | 0.18 | 0.72 | 1.54|

Note: Same as in earlier table
Table 7 Z values obtained for temperature over sites of Godavari River basin

| Name of site | Maximum temperature | Minimum temperature |
|--------------|---------------------|---------------------|
|              | ANNU | WINT | PREM | MONS | POST | ANNU | WINT | PREM | MONS | POST |
| 1 Aurangabad | −0.94 | 0.60 | 0.39 | −1.83 | 1.21 | 5.28 | 4.38 | 4.46 | 5.16 | 2.01 |
| 2 Betul      | 3.81  | 1.97 | 2.86 | 2.41 | 3.56 | 1.70 | 0.68 | 1.05 | 2.80 | −0.26 |
| 3 Hyderabad  | 2.56  | 1.54 | 2.31 | 1.48 | 2.28 | 3.14 | 2.95 | 2.44 | 2.63 | 1.55 |
| 4 Jagdalpur  | 2.48  | 1.75 | 0.33 | 1.83 | 2.93 | −0.75 | −1.61 | −0.94 | 1.56 | −1.04 |
| 5 Nagpur     | 2.03  | 0.18 | 0.64 | 0.99 | 2.23 | 2.33 | 2.64 | 1.25 | 2.40 | 1.26 |
| 6 Yeotmal    | −2.34 | −1.07 | −1.14 | −1.33 | −1.95 | −1.88 | −2.40 | −1.90 | −0.3 | −1.3 |
| 7 Ramgundam  | −1.37 | −0.95 | −0.60 | −0.20 | 1.06 | −1.30 | −0.61 | −1.31 | 0.35 | −1.93 |

Note: Same as in earlier table

Table 8 Z values obtained for wind speed over Godavari River basin

| Time scale   | Aurangabad | Betul | Hyderabad | Jagdalpur | Nagpur | Yeotmal | Ram |
|--------------|------------|-------|-----------|-----------|--------|---------|-----|
| January      | −4.1       | −4.5  | −2.6      | −5.5      | −6.1  | −2.9    | −2.3|
| February     | −4.8       | −4.8  | −2.3      | −5.4      | −6.4  | −4.1    | −2.6|
| March        | −5.3       | −5.3  | −2.3      | −5.3      | −7.3  | −3.9    | −3.4|
| April        | −5.3       | −5.5  | −3.7      | −6.0      | −6.3  | −4.4    | −3.3|
| May          | −5.0       | −6.5  | −2.5      | −5.6      | −6.7  | −3.9    | −3.7|
| June         | −5.8       | −6.4  | −5.3      | −5.3      | −7.3  | −5.1    | −4.1|
| July         | −5.4       | −5.4  | −5.4      | −6.0      | −6.6  | −4.6    | −2.5|
| August       | −4.8       | −5.7  | −4.8      | −4.6      | −6.5  | −4.1    | −2.1|
| September    | −5.8       | −5.9  | −3.3      | −4.5      | −7.0  | −4.2    | −3.6|
| October      | −6.1       | −4.7  | −1.0      | −2.8      | −6.1  | −2.6    | −3.5|
| November     | −4.6       | −4.5  | −1.4      | −2.3      | −6.1  | −4.3    | −3.9|
| December     | −5.2       | −3.9  | −2.4      | −4.7      | −6.8  | −3.9    | −3.0|
| Annual       | −5.6       | −7.2  | −5.7      | −6.6      | −8.4  | −5.0    | −4.1|
| Winter       | −4.8       | −5.1  | −2.7      | −5.7      | −7.1  | −3.9    | −2.8|
| Pre-monsoon  | −5.5       | −6.4  | −3.4      | −6.1      | −7.5  | −4.5    | −3.8|
| Monsoon      | −5.8       | −7.4  | −6.1      | −6.1      | −7.9  | −4.7    | −3.3|
| Post-monsoon | −5.0       | −5.0  | −2.6      | −3.8      | −6.7  | −4.8    | −3.5|

Note: Bold numbers are statistically significant at 5% level of significance obtained through the MK test. Ram denotes Ramagundam. Italics numbers are non-significant at 5% level of significance.

Statistically significant at 99% confidence limit. However, on monthly time scales, only one station (Hyderabad) witnessed no trend in wind speed even at 10% level of significance in the months of October and November. McVicar et al. (2012) reported significant decreases in annual wind speed at the rate of (−) 0.027 m/s/annum obtained through the Theil-Sen’s non-parametric test over the entire Godavari basin. The range of annual wind speed decreases varied from (−) 0.022 to (−) 0.047 m/s/annum for the selected sites in the Godavari basin.

Bright sunshine duration data are recorded at two sites (Hyderabad and Nagpur) on monthly basis since 1969. Both upward and downward trends in actual sunshine duration were observed at both the sides of the Godavari basin. However, statistically significant decreasing trends in actual sunshine duration at 95% confidence limit were observed over both the sites of the basin in different durations: annual; seasonal: winter; and monthly: January. Hyderabad and Nagpur witnessed significant decreasing trends in bright sunshine duration at the rate of (−) 0.184 h per decade and (−) 0.099 h per decade, respectively. Nagpur (Hyderabad) station witnessed statistically significant decreasing trends at 5% level of significance in post-monsoon (monsoon) season and during the months from October to December (in February and April). However, both the sites witnessed no trends in bright sunshine duration, even at 10% level of significance, in pre-monsoon season. These results indicate the presence of seasonality in the observed trends in sunshine duration over the Godavari River basin. On the other hand, both the sites witnessed no trends in bright sunshine duration over Godavari River basin in the remaining months, i.e. March and May to September (see Table 9).
4.2.3 Searching evidence for the existence of evaporation anomaly

The Intergovernmental Panel on Climate Change (IPCC) has stated in its reports that the increase in the global temperature is due to the increased anthropogenic emission of greenhouse gases. According to the IPCC (2007, 2013), increasing concentrations of global greenhouse gases, enhanced positive radiative forcing and global warming are all significantly affected by human activities. As the temperature is one of the significant factors in driving the evaporation mechanism, increase in temperature would enhance the evaporation process. However, evaporation anomalies have been observed around the world where the evaporation rate contradicts the increasing temperature. It is interesting to note that the decreases in $E_{\text{pan}}$ in the Godavari basin despite the reported temperature increase can be attributed to the other dominating climatic parameters, i.e. wind speed, humidity, sunshine hours, etc. Stepwise regression analysis showed that wind speed (RH$_{\text{max}}$) was found to be the main driving factor, which affected trends in $E_{\text{pan}}$ in winter, pre-monsoon and monsoon (post-monsoon) over Godavari basin. On annual time scale, wind speed followed by the RH$_{\text{min}}$, RH$_{\text{max}}$ and $T_{\text{max}}$ was found to be the main causative parameters of the observed trends in $E_{\text{pan}}$ over Godavari basin. On the monthly time scale, wind speed followed by relative humidity (relative humidity followed by wind speed) was found to be two main causative parameters of the observed trends in $E_{\text{pan}}$ during the months of January to June (July to December) over Godavari basin (see Tables 10 and 11).

| Time scale | Decreasing trends | Increasing trends |
|------------|-----------------|-----------------|
|            | $E_{\text{pan}}$ | RH | Wind | Sun | $T_{\text{min}}$ | $T_{\text{max}}$ | $E_{\text{pan}}$ | RH | Wind | Sun | $T_{\text{min}}$ | $T_{\text{max}}$ |
| January    | 3               | 0   | 7    | 2   | 1   | 0               | 0               | 4   | 0   | 2   | 0               |
| February   | 5               | 0   | 7    | 2   | 0   | 0               | 0               | 3   | 0   | 3   | 0               |
| March      | 7               | 0   | 7    | 0   | 0   | 0               | 0               | 6   | 0   | 3   | 0               |
| April      | 7               | 0   | 7    | 1   | 0   | 0               | 0               | 5   | 0   | 2   | 1               |
| May        | 7               | 0   | 7    | 0   | 0   | 0               | 0               | 3   | 0   | 3   | 1               |
| June       | 5               | 0   | 7    | 0   | 0   | 0               | 0               | 2   | 0   | 2   | 0               |
| July       | 6               | 0   | 7    | 0   | 0   | 0               | 0               | 2   | 0   | 5   | 1               |
| August     | 4               | 0   | 7    | 0   | 0   | 0               | 0               | 5   | 0   | 1   | 0               |
| September  | 5               | 0   | 7    | 0   | 1   | 0               | 0               | 1   | 0   | 5   | 3               |
| October    | 4               | 0   | 6    | 1   | 0   | 1               | 0               | 5   | 0   | 3   | 1               |
| November   | 6               | 0   | 6    | 1   | 0   | 0               | 0               | 6   | 0   | 2   | 3               |
| December   | 4               | 0   | 7    | 1   | 1   | 0               | 0               | 3   | 0   | 0   | 4               |
| Annual     | 6               | 0   | 7    | 2   | 0   | 1               | 0               | 6   | 0   | 4   | 4               |
| Winter     | 5               | 0   | 7    | 2   | 1   | 0               | 0               | 5   | 0   | 3   | 1               |
| Pre-monsoon| 7               | 0   | 7    | 0   | 0   | 0               | 0               | 7   | 0   | 2   | 2               |
| Monsoon    | 6               | 0   | 7    | 0   | 0   | 0               | 0               | 5   | 0   | 4   | 1               |
| Post-monsoon| 5              | 0   | 7    | 1   | 0   | 1              | 0               | 5   | 0   | 1   | 4               |

Note: RH denotes relative humidity

| Parameters | Different durations |
|------------|-------------------|
|            | Annual (i) (ii) (iii) | Winter (i) (ii) (iii) | Pre-Monsoon (i) (ii) (iii) | Monsoon (i) (ii) (iii) | Post-Monsoon (i) (ii) (iii) |
| WIND       | 4      | 1      | 3      | 2      | 1      | 4      | 1      | 3      | 1      | 1      | 1      |
| RHMAX      | 2      | 1      | -      | -      | -      | -      | 2      | -      | -      | 1      | 2      | -      |
| MINRH      | 2      | -      | 1      | -      | 2      | -      | 2      | 1      | -      | -      | -      | 1      |
| MEANRH     | -      | -      | -      | -      | -      | -      | 1      | -      | 1      | -      | -      | -      |
| SUNSHINE   | -      | -      | -      | -      | -      | -      | -      | -      | -      | -      | -      | -      |
| MAXTEMP    | 2      | 1      | 1      | 2      | -      | -      | -      | -      | -      | -      | -      | -      |
| MINTEMP    | 1      | 1      | -      | -      | -      | -      | 1      | -      | -      | -      | -      | 1      |
| MEANTEMP   | 1      | -      | -      | -      | 1      | -      | -      | -      | -      | 1      | -      | -      |
4.3 Spatial variation in pan evaporation and changes in climatic variable

Godavari River is a transboundary river which partially covers the States of Central, Eastern and Southern India. Elevation variation in the river basin varies from 1067 m at the origin point to 329 m at the confluence point in Bay of Bengal. Thus, spatial variation map of pan evaporation was prepared in annual and seasonal time scales to find out the seasonal variations in these parameters. Figure 4a shows the E_{pan} map of Godavari River basin in annual scale and seasonal scales, i.e. winter, pre-monsoon, monsoon and post-monsoon. At the middle Godavari region where moderate elevation prevails, annual E_{pan} reaches to the highest value of 2225.42 mm/year whereas 1429.38 mm/year at the higher elevation region. Spatial map of the seasonal variation of E_{pan} shows that winter and post-monsoon months have the similar E_{pan} values ranging from 297.25 (maximum value) to 196.77 mm (minimum value). Pre-monsoon and monsoon months have higher evaporation as compared to the E_{pan} in winter and post-monsoon months, which ranges from 848.4 to 546.72 mm.

To determine the magnitude of changes in climatic variables in these regions, Sen’s slope test was applied to wind speed and average temperature series at annual and seasonal time scales. Magnitudes of trends in average temperature at the annual and seasonal scales are shown in Fig. 4b. Aurangabad region shows decreased magnitude in annual temperature and positive trend with magnitude of 0.25 °C/decade; the winter season shows positive change in temperature with maximum magnitude of 0.25 °C/decade in Nagpur and Betul stations whereas decreasing trend with magnitude of –0.22 °C/decade at Aurangabad and Yeotmal stations. Figure 4c shows the spatial map of the trends in wind speed for all the seasons. It is evident that wind speed has a uniform negative trend in the basin. Evaporation is a complex process, which is governed by several climatic factors. Trend analysis of the pan evaporation time series shows a declining trend on the contrary to the rising temperature, which is evident from the spatial map of the pan evaporation and trends in the wind speed and temperature.

4.4 Change point analysis for climatic variables

Change point analysis of the observed E_{pan} was determined in monthly, annual and seasonal time scales, i.e. winter, pre-monsoon, monsoon and post-monsoon. Observed E_{pan} data from seven stations of Godavari River basin were analysed by using Pettitt’s test for probable change year detection; mean of sub-series before the change year and after the change point year were also calculated for assessment of the change in the mean E_{pan}. Table 12 shows the change point years along with mean of series before and after the change point year at monthly time scale. It is evident from the table that the probable year of change in the E_{pan} in the month of January is observed between 1985 and 1992 with the exception of Jagdalpur station, where 1978 was found as probable year of change. Change in the mean of E_{pan} for these stations before and after the change point years show that the E_{pan} values have declined after the change point year. At Hyderabad station, mean E_{pan} was found to be 155.4 mm whereas after the change point mean E_{pan} was calculated to be 110.4 mm. Jagdalpur station shows increase in E_{pan} (81.8 mm) after the change year. Similarly, for the months of February and March, the probable change year was observed as 1989–1990 (Aurangabad, Nagpur and Betul). The months of April, May and June records rise in the mean of the sub-series after the change point year as compared to the sub-series before the year of change, with majority of stations having change years observed between 1987 (Jagdalpur) and 2001 (Ramagundam). Jagdalpur station observed increased mean in E_{pan} sub-series after the change point year for the months from July to December. For Hyderabad station, most of the months show 1991–1992 as probable year of change, whereas months of March and June

Table 11 Stepwise regression for causal parameters of E_{pan} in monthly time scales

|        | January | February | March | April | May | June | July | August | September | October | November | December |
|--------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|
| WIND   | i       | ii       | iii   | i     | ii  | iii  | i    | ii     | iii       | i       | ii       | iii      |
| RHMAX  | 3       | –        | –     | 2     | –   | 1    | –    | –      | 1         | –       | –        | –        |
| MINRH  | –       | 1        | i     | –     | 1   | –    | 1    | –      | –         | –       | –        | –        |
| MEANRH | –       | –        | –     | 1     | –   | 1    | –    | 1      | –         | –       | –        | –        |
| SUNSHINE| –      | –        | –     | –     | –   | –    | –    | –      | –         | –       | –        | –        |
| MAXTEMP| 1       | i        | –    | 1     | 2   | 1    | 1    | –      | 2         | –       | –        | –        |
| MINTEMP| –       | –        | –     | –     | –   | 2    | –    | –      | –         | –       | –        | –        |
| MEANTEMP| –     | –        | –     | –     | –   | –    | –    | –      | –         | –       | –        | –        |
having no significant change year. At Betul station, the months of May and June show 1997–1998 as probable year of change and remaining months recorded probable change year in 1991–1992. Probable year of change in $E_{\text{pan}}$ at Nagpur station was observed from 1984 to 1989 and mean of sub-series show decline in mean $E_{\text{pan}}$ after the change point year. Aurangabad station shows probable year of change from 1990 to 1992 whereas the months from June to December does not show any significant change. Jagdalpur being the exceptional station amongst others as the month from July to December shows...

Fig. 4  

a Spatial variations of $E_{\text{pan}}$ (mm) over Godavari River basin at annual and seasonal scales. 

b Spatial variations of $T_{\text{avg}}$ trends magnitude ($^\circ$C/decade) over Godavari river basin at annual and seasonal time scales. 

c Spatial variations of wind speed trends magnitude (m/s/decade) over Godavari River basin at annual and seasonal scales.
increased mean value of $E_{\text{pan}}$ after the change point year; in July the mean of $E_{\text{pan}}$ before the change point year (1999) was observed to be 96.4 mm which increased to 128.3 mm after the change point year. Similar pattern was observed in months of October, November and December in pre-change years when mean was observed as 10.8, 80.0 and 75.2 mm, respectively, which increased after the change point year as 117.0, 93.6 and 94.2 mm, respectively.

Table 12 Change detection test results for the stations at monthly time scale

|          | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Hyderabad| CPY | 1992| 1992| 2000| 1992| 1993| 2001| 1988| 1991| 1991| 1992| 1991|
| Mean1    | 155.4| 181.9| 233.0| 271.1| 302.9| 200.3| 182.6| 157.8| 162.9| 168.0| 147.9| 136.5|
| Mean2    | 110.4| 123.3| 153.5| 197.7| 218.4| 135.0| 134.0| 116.1| 114.5| 114.7| 104.7| 103.1|
| Betul    | CPY | 1991| 1991| 1992| 1992| 1997| 1998| 1993| 1993| 1992| 1991| 1990|
| Mean1    | 103.9| 114.3| 153.7| 185.3| 208.4| 156.4| 119.9| 102.0| 118.1| 132.6| 111.0| 106.0|
| Mean2    | 85.8| 86.0| 95.2| 108.1| 138.0| 104.9| 77.5| 68.1| 78.3| 92.5| 83.9| 83.3|
| Nagpur   | CPY | 1985| 1989| 1988| 1990| 2001| 1999| 1984| 1989| 1984| 1987| 1988|
| Mean1    | 115.2| 133.1| 205.2| 254.1| 287.6| 200.0| 137.6| 113.5| 132.6| 146.9| 123.3| 110.5|
| Mean2    | 102.7| 117.6| 161.7| 190.3| 156.2| 150.4| 107.4| 97.9| 116.3| 125.7| 102.9| 92.8|
| Aurangabad| CPY | 1990| 1990| 1990| 1993| 1992| 2003| 2004| 2005| 2005| 2005| 2002|
| Mean1    | 147.6| 180.7| 273.1| 319.7| 375.8| 202.9| 137.5| 114.6| 128.9| 151.8| 118.9| 122.3|
| Mean2    | 92.8| 110.7| 161.9| 205.1| 224.0| 128.3| 67.2| 62.0| 70.0| 99.2| 72.0| 72.5|
| Jagdalpur| CPY | 1978| 1997| 1997| 1994| 1989| 1987| 1999| 1999| 1999| 1978| 1999|
| Mean1    | 81.8| 115.7| 173.6| 207.9| 228.4| 161.4| 96.4| 74.4| 95.1| 100.8| 80.0| 75.2|
| Mean2    | 88.0| 108.2| 160.3| 174.0| 190.7| 140.8| 128.3| 90.6| 115.9| 117.0| 93.6| 94.2|
| Ramagundam| CPY | 1989| 2001| 2001| 2001| 2001| 2000| 2000| 2001| 1993| 1989| 1990|
| Mean1    | 103.8| 122.7| 183.5| 228.2| 279.5| 196.9| 121.8| 104.0| 111.9| 116.3| 98.3| 95.9|
| Mean2    | 74.9| 86.8| 117.8| 138.0| 148.8| 108.0| 94.6| 71.3| 89.3| 94.0| 77.8| 71.1|

CPY change point year, Mean1 mean of $E_{\text{pan}}$ before change point year, Mean2 mean of $E_{\text{pan}}$ after change point year
Pettitt’s test for change detection was applied to annual values of $E_{pan}$ as well as the $E_{pan}$ values of four different seasons, i.e. winter, pre-monsoon, monsoon and post-monsoon along with the mean of sub-series before the change point year and after the change point year. Table 13 shows the values of the change detection tests for the $E_{pan}$ obtained from the Pettitt test in annual and seasonal time scales. Hyderabad station records the probable change year in 1992–1993 at annual, winter, pre-monsoon and post-monsoon scales whereas monsoon season records the 1989 as probable year of change. Mean of the sub-series shows uniform decreasing trend across all the seasons. Annual $E_{pan}$ values at Hyderabad show value of 2314.91 mm before the change point year (1992) which decreases to 1685.25 mm. Similarly monsoon season pan evaporation shows 904.37 mm which decreases to 644.15 mm after the year 1989. Betul and Jagdalpur stations show change point year between the years from 1987 to 1994 except the post-monsoon season for Jagdalpur (1999) when the mean.

Table 13 Change detection test results for the stations at annual and seasonal time scale

| Station       | CPY       | Annual | Winter | Pre-Monsoon | Monsoon | Post-Monsoon |
|---------------|-----------|--------|--------|-------------|---------|-------------|
| Hyderabad     | 1992      | 1992   | 1993   | 1989        | 1992    |
| Mean1         | 2314.91   | 337.26 | 817.78 | 904.37      | 281.11  |
| Mean2         | 1685.25   | 233.65 | 593.41 | 644.15      | 208.22  |
| Betul         | 1992      | 1991   | 1992   | 1992        | 1991    |
| Mean1         | 1631.57   | 218.15 | 561.15 | 642.30      | 217.11  |
| Mean2         | 1120.60   | 171.74 | 349.86 | 429.80      | 167.41  |
| Nagpur        | 1989      | 1985   | 1989   | 1984        | 1985    |
| Mean1         | 1984.11   | 251.71 | 782.63 | 756.05      | 239.42  |
| Mean2         | 1593.48   | 220.56 | 558.22 | 620.12      | 195.72  |
| Betul         | 2004      | 1990   | 1993   | 2004        | 2004    |
| Mean1         | 2078.67   | 328.28 | 943.74 | 733.60      | 240.09  |
| Mean2         | 1278.00   | 203.55 | 593.68 | 425.27      | 139.37  |
| Nagpur        | 1989      | 1993   | 1994   | 1997        | 1999    |
| Mean1         | 1550.38   | 205.29 | 601.65 | 562.29      | 162.55  |
| Mean2         | 1444.50   | 194.93 | 525.49 | 537.96      | 201.41  |
| Betul         | 2000      | 1989   | 2001   | 2000        | 1988    |
| Mean1         | 1725.08   | 244.54 | 691.26 | 635.22      | 196.78  |
| Mean2         | 1266.60   | 171.13 | 404.60 | 491.85      | 148.86  |

$CPY$ change point year, $Mean1$ mean of $E_{pan}$ before change point year, $Mean2$ mean of $E_{pan}$ after change point year

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![Graphs](image-url)  
*Fig. 5 Change point year with trend line before and after the change year at annual time scale*
of post-change year is also observed higher than the previous years. Similarly, Nagpur, Aurangabad and Ramagundam also show decrease in $E_{\text{pan}}$ value after the change point years.

Figure 5 shows the time series of annual evaporation with trend line of sub-series before the change point year and after the change point year. It is evident from the figure that trend is decreasing continuously and change in the mean is observed mostly in the decade of 1990s. Jagdalpur station shows increase in mean annual evaporation after the change point year whereas Hyderabad, Betul and Nagpur show uniform decrease in annual evaporation.

Seasonal pan evaporation time series with their trend lines for the sub-series of pre-change point year and post-change point year is shown in Fig. 6. Figure 6 shows the time series of winter, pre-monsoon, monsoon and post-monsoon seasons with change point years. Hyderabad station shows uniform declining trend in $E_{\text{pan}}$ with a uniform shift in the mean across the seasons during the 1990s decade. On contrary to the declining trend in Hyderabad, Betul station shows the shift in evaporation value but the trend in sub-series possesses a rising trend with mean being lesser in the post-shift year sub-series. Nagpur station shows shift in the series in mid of 1980s decade in all the season and rising trend was observed in after the shift year sub-series. Aurangabad station does not show significant shift in the series during the monsoon and post-monsoon seasons whereas winter and pre-monsoon seasons reflect shift in the mean during 1988 and 1993, respectively. Uniform shift in seasonal time

![Fig. 6](image-url)  
Fig. 6 Change point year with trend line before and after the change year at seasonal time scale
series was observed at Jagdalpur station but Ramagundam station shows no shift in pre-monsoon and monsoon seasons.

It was observed from the study that an evaporation paradox exists in the Godavari River basin as temperature trends shows rising trends but contrary to the established proposition decreasing trend in evaporation was observed. Change point detection of evaporation series shows break-point year in the 1990s for most of the stations. Results of this study are consistent with the findings of similar studies carried out in different river basins (Yan et al. 2019; Jhajharia et al. 2009).

5 Conclusions

Trends in the E_{pan} were investigated in annual, monthly and seasonal time scales over the Godavari basin, the largest southern peninsular river basin of India, by using the non-parametric Mann–Kendall test in annual, seasonal and monthly time scales. T_{max} (T_{min}) remains practically trendless in different time scales: monthly—all except December (all except July and September); and seasonal—all except post-monsoon (all except monsoon) over Godavari basin. Statistically significant increasing trends witnessed in T_{max} (in December and post-monsoon) and T_{min} (in July and September and monsoon) indicate the presence of an element of seasonal cycle in temperature over the Godavari River basin. Shivam et al. (2017) also reported increasing trends in maximum and minimum temperatures in annual and monthly time scales over the Subansiri River basin, northeast India. On the other hand, decreasing trends are witnessed in T_{min} in April and in the pre-monsoon season at 7 and 8 stations, respectively, out of 35 selected sites in the Godavari basin. On seasonal and annual time scales, statistically significant decreasing trends in E_{pan} were witnessed in all seven sites in pre-monsoon season and in six sites in annual and monsoon season in the Godavari basin. Statistically significant decreasing (increasing) trends in wind speed (relative humidity) in pre-monsoon season and in the month of March at these seven sites support the observed decline in the evaporative demand in the basin. Wind speed followed by relative humidity was found to be two main causative parameters of the observed decline in the E_{pan} under the warmer environments in the basin. Change point analysis of the evaporation and several climatic parameters show 1990s as the probable year of change, which is considered as the era of industrialization which escalate the global warming and climate change phenomena.

Our results have potential for the adoption of climate-related changes in the Godavari Water Dispute Tribunal (GWDT) award in future by the policy makers as currently the award related to the optimal utilization of Godavari River shared by six states is adopted permanently. Singh et al. (2008) stated that the awareness about the hydrological response of a river basin under changed climatic conditions may be helpful in modifying the present practices of planning, designing and management of water resources projects. Moreover, a climate-related study at the basin scale will help in combating the adverse impacts, if any, on rainfed agriculture and forest dependent tribal local communities due to climate change-induced changes in the Godavari basin. Results of the present research may assist water planners in establishing exact amount of apportioned waters to each beneficiary states of Godavari under changing climatic conditions as analyses of catchment hydrological dynamics require estimates of evaporative demand in the basin.

Author contribution All authors have contributed equally and have read it thoroughly and approve the manuscript.

Data availability Authors would like to thank India Meteorological Department for providing the meteorological data.

Code availability Not applicable.

Declarations

Ethics approval Authors declare that all the accepted principles of ethical and professional conduct have been followed in this research work.

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