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Research Article

Keywords: Pan evaporation, Trend, Pettitt's Test, Godavari basin, Causal Meteorological Parameters

Posted Date: April 27th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-458780/v1

Version of Record: A version of this preprint was published at Theoretical and Applied Climatology on July 12th, 2021. See the published version at https://doi.org/10.1007/s00704-021-03707-9.

Pan Evaporative Changes in Trans-boundary Godavari River basin, India

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Abstract

Pan evaporative changes are one of the key components of water resources management of a basin under changing climate and anthropogenic-induced warming. This study was undertaken for trans-boundary Godavari River (India) to identify trends through the Mann-Kendall (MK) test after removing the effect of significant lag-1 serial correlation from the climatic time-series by pre-whitening in pan evaporation (E_{pan}) and in the probable causative meteorological parameters responsible for evaporative climatic changes in a large basin. Further, the Pettitt's test was applied on E_{pan} time series for estimating the change point year of E_{pan} to find out the effective year when the change in pattern started reflecting in the time-series. At seasonal (monthly) time scales, statistically significant decreasing trends in E_{pan} were witnessed in pre-monsoon season (in the months of March, April and May) over all the seven sites of the Godavari basin. Four sites witnessed statistically significant increasing trends in Tmin (Tmax) in July (December) and in monsoon (post monsoon) season in the basin. Statistically significant decreasing (increasing) trends in wind speed (relative humidity) in pre-monsoon and in 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 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_{pan} under the warmer environments in the basin. Pettitt's test shows year 1991-1992 to be the probable year of change in the E_{pan} in the Godavari river basin.

Keywords: Pan evaporation; Trend; Pettitt's Test; Godavari basin; Causal Meteorological Parameters.

1.0 Introduction

Evaporation, one of the main components of hydrologic cycle, which 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. The process of evaporation is a complex function of several parameters and change in one parameter can influence other parameter(s). Changes in air temperature can modify the saturation vapor pressure, which in turn may alter the evaporation rate as well (Dinpashoh *et al.*, 2011).

The global air temperature has increased by 0.6°C in 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 part of India for analysis of trends in climatic parameters. Shivam *et al.* (2017) analysed the trends in rainfall events over a river basin of north-eastern India and found significant rising trend in annual rainfall with increase in extreme rainfall events. Goyal (2014) studied the trend and change point analysis in long-term rainfall data over Assam state of India and found 1959 as probable year of change in rainfall pattern. Jaiswal *et al.* (2014) conducted change detection study on climatic parameter over Raipur district of India and found significant rising trend in summer temperature with rising evaporation process attributed to increased wind speed and temperature. Krishan *et al.* (2017) analysed the trends in rainfall and dry/wet years over a canal command area of Northern India. Study found a significant decreasing trend in annual and monsoon rainfall. Hadi and Tombul (2017) reported significant increasing trend by using the Mann-Kendall test in temperature with 0.88 °C/century whereas precipitation showed insignificant increasing trends over Turkey.

Jhajharia (2012) reported rise in air temperature over a southern peninsular river basin of India using the temperature data of 35 sites located indifferent sub-basins of the Godavari River. The reported temperature rise in the Godavari convinced to establish if evaporation may have increased in the warmer climates affecting water availability in the Godavari basin. Thus, Godavari River is selected with the objective of studying trends in pan evaporation (E_{pan}) through the Mann-Kendall (MK) test in annual, seasonal and monthly time scales in the current study. The procedure of pre-whitening was applied to remove the effect of significant lag-1 serial correlation, if any, from original time-series of the E_{pan}. Trends were also identified in temperature, wind speed, relative humidity and sunshine duration by using the MK test. Further, the stepwise regression method is used to search for the principal climatic variables associated with E_{pan} and possibly explain the underlying mechanisms of observed pan evaporative changes in the Godavari basin.

2. Material and Methods

2.1 Details of study and meteorological data

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 Triambakeshwar in Nasik district of Maharashtra (Jain *et al.*, 2007). The basin extends over about 9.5% of the total geographical area of India. Godavari River passes through seven states, namely, Maharashtra, the newly created state of 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. Recently, 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 among the 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 in the basin (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°C to 35.5°C in different parts of the Godavari basin (Jhajharia et al., 2014). The monthly data of E_{pan} were obtained from the India Meteorological Department (IMD), Pune (Maharashtra), for different periods, especially from 1969-2007, at seven stations, namely, Aurangabad, Betul, Hyderabad, Jagdalpur, Nagpur, Yeotmal and Ramagundam located in different sub-basins of the Godavari. The details and location of selected sites are given in Table 1 and Fig. 1, respectively. The monthly data set were used to obtain the annual and seasonal values of pan evaporation for these sites of the basin. The monthly and annual average data of total E_{pan} of all the stations of the basin are given in Table 2. The total average annual E_{pan} values vary in the range of 1400.80 mm to 2129.70 mm in the Godavari basin.

Location of Fig. 1

Location of Table 1

Location of Table 2

2.2 Trend Analysis

In the present study, the MK test was used for detecting trends in E_{pan} 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 beginning, we tested the significance of lag-1 serial correlation (r1) for the E_{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_{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 analysis details about the pre-whitening might be referred in Kumar *et al.* (2009), Partal and Kahya (2006), Dinpashoh *et al.* (2011) and Jhajharia *et al.* (2012, 2014). 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 equation 1 and 2 respectively.

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

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

The MK statistic (Z) can be computed as

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & S < 0 \end{cases} \quad (2)$$

If $-Z_{1-\alpha/2} \leq Z \leq Z_{1-\alpha/2}$, then the null hypothesis of no trend can be accepted at significance level of α. Otherwise, the null hypothesis can be rejected and alternative hypothesis can be accepted at significance level of α.

2.3 Change Point Detection

The Pettitt (1979) test is a non-parametric change detection test, which is used finding 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:

$$U_t = \Sigma_{i=1}^{t} \Sigma_{j=t+1}^{n} sign(x_t - x_j) \quad (3)$$

$$sign(x_t - x_y) = \begin{cases} 1 \ldots\ldots\ldots if > 0 \\ 0 \ldots\ldots\ldots if = 0 \\ 1 \ldots\ldots\ldots if < 0 \end{cases} \quad (4)$$

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

$$K = max(U_t) \quad (5)$$

$$\rho = \exp[\frac{-K}{n^2 + n^3}] \quad (6)$$

When ρ 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:

$$P = 1 - \rho \quad (7)$$

3. Results and discussion

Trends in E_{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 below as follows.

3.1. Analysis of temporal trends in E_{pan}

The records of E_{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 E_{pan} values varied from about 1401.0 mm to 2606.4 mm over the basin. The observed total E_{pan} of the Godavari basin as a whole is found to be about 1877.4 mm per annum. The average total E_{pan} during the winter (in the months of December and January) is in the range of around 106–114 mm over the whole basin. The mean monthly E_{pan} over the basin varies in the range of around 198–279 mm during the months of March to May in the pre-monsoon season. The monthly E_{pan} attain the peak values in the month of May for most of the sites in the Godavari basin. Thereafter, the monthly E_{pan} values decreased gradually during the monsoon from the months of June and July, and reaching the lowest E_{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 Godavari basin. However afterwards, the monthly E_{pan} values increased a little bit in September and October due to comparatively drier climate in these two months in Godavari basin. On a seasonal time scale, the E_{pan} values in the pre-monsoon season accounted for about 38.1% of the annual E_{pan} in only three months. However, E_{pan} values in the winter and post-monsoon seasons accounted for about 25.2% of the annual E_{pan} during four months from November to February in the basin.

The trends in E_{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_{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_{pan} in annual time scale. However, about 86% of the stations witnessed statistically significant decreasing trends at 1% level of significance in E_{pan} in annual time scale. Fig. 2 shows the E_{pan} time series and the trend lines of different sites in the Godavari basin indicating downward trends in annual time scale. In annual time scale, statistically significant decreasing trends in total pan evaporation were witnessed in the range of (-)18.1 to (-)48.0 mm/annum over different sites of the basin. On seasonal time scale, E_{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_{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_{pan} data in the basin as the strongest E_{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_{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 significant downward trends in the E_{pan} during the months of June, July and November in the basin. On the other hand, half of the sites witnessed no trends in E_{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_{pan}, although statistically non-significant, during the months of July to December and January (months comprising the monsoon and post-monsoon seasons) in the basin.

3.2. Analysis of temporal trends in other climatic parameters

3.2.1 Trends in Relative Humidity and Temperature

The data of the morning relative humidity (RH_{max}) and the afternoon RH (RH_{min}) are usually recorded at 8.30 and at 17.30 hours Indian standard time (IST), respectively at seven IMD meteorological observatories maintained in the basin. The mean RH, i.e., RH_{mean}, data were obtained by taking the arithmetic average of the morning and afternoon values of RH of a given site for any time scale. The annual RH_{mean} is found to ranging from 40% to 70% in the Godavari river basin. Fig. 3 shows the time series of RH_{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_{mean} over seven sites located in Godavari basin at monthly, annual and seasonal time scales. Out of the selected seven sites, five sites witnessed upward trends in RH_{mean} at 5% level of significance in annual time scale in the basin. Another station (Hyderabad) witnessed increasing trend in annual duration in RH_{mean}, but at 10% level of significance. Thus, significant increases in the RH_{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_{mean} trends are almost similar to 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_{mean} in pre-monsoon season (in winter, monsoon and post-monsoon seasons). On monthly time scale, it can be inferred from Table 4 that only upward trends in RH_{mean} were witnessed over all the sites during the months from January to October. However, both upward and downward trends were witnessed in November and December in RH_{mean}. On monthly time scale, five or six sites in the Godavari basin witnessed statistically significant upward trends in RH_{mean} at 5% or 10% level of significance during the months from January to March, May, August, October and November. However, only50% of the stations witnessed statistically significant increasing trends in the months of April, June, July, September and December in RH_{mean} over the Godavari basin. The significant increases in RH_{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 the Godavari 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) temperature and minimum (night) temperature in monthly, annual and seasonal time scales were also identified through the non-parametric MK test. Table 5(a) to 5 (c) 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 each (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.

3.2.2 Trends in Wind Speed and Sunshine Duration

Table 6 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 at 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 twelve months as most of the trends are 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/sec/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 m/sec/annum to (-) 0.047m/sec/annum for the selected sites in the Godavari basin.

Bright sunshine duration data are recorded at two sites (Hyderabad and Nagpur) located in the Godavari River basin on monthly basis since 1969. Table 6 shows the values of the Z statistic obtained through the MK test for identifying trends in actual bright sunshine duration at Hyderabad and Nagpur sites located in Godavari basin at monthly, annual and seasonal time scales. 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 hours per decade and (-) 0.099 hours 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 monthly time scale, both the sites (one site each) witnessed statistically significant decreasing trends in bright sunshine duration in the month of January (in the months of February and April at Hyderabad; and in the months of October to December at Nagpur) over 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.

3.2.3 Searching evidence for the existence of evaporation anomaly

IPCC (2007) has stated in its report that the increase in the global temperature is due the increased anthropogenic emission of greenhouse gases. As the temperature is one of the significant factor 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_{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_{max}) was found to be the main driving factor, which affected trends in E_{pan} in winter, pre-monsoon and monsoon (post-monsoon) over Godavari basin. On annual time scale, wind speed followed by the RH_{min}, RH_{max} and T_{max} were found to be the main causative parameters of the observed trends in E_{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_{pan} during the months of January to June (July to December) over Godavari basin.

3.3 Spatial variation in Pan Evaporation and Changes in Climatic Variable

Godavari River is a trans-boundary 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 for annual and seasonal timescale to find out the seasonal variation in these parameters. Fig. 4a shows the E_{pan} map of Godavari river basin at annual scale and four different 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 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 are having the similar E_{pan} values ranging from 297.25 mm (maximum value) to 196.77 mm (minimum value). Pre-monsoon and monsoon months are having higher evaporation as compared to winter and post-monsoon months which ranges from 848.4 mm to 546.72 mm.

<<<<<<<<<<<<<<<<<<Fig 4a>>>>>>>>>>>>>>>>>>>

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 scale. Magnitudes of trends in average temperature at annual and seasonal scale are shown in Figure 4b. Aurangabad region shows decreased magnitude in annual temperature and positive trend with magnitude of 0.25°C/decade, 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 trend in wind speed for all the seasons, from the figure it is evident that wind speed is having 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 declining trend on the contrary to the rising temperature trend which is evident from the spatial map of the evaporation and trends of the wind speed and temperature.

<<<<<<<<<<<<< Fig 4b>>>>>>>>>>>>>>>>

<<<<<<<<<<<<< Fig 4c>>>>>>>>>>>>>>>>

3.4 Change point analysis for climatic variables

Change point analysis of the observed pan evaporation was determined at monthly, annual and seasonal time scales, i.e., winter, pre-monsoon, monsoon and post monsoon months. Observed E_{pan} data from six stations of Godavari river basin were analyzed for using Pettitt's test for probable change year detection, mean of subseries before the change year and after the change point year were also calculated for assessment of the change in mean. Table 9 shows the change point years along with mean of series before and after the change point year at monthly timescale. It is evident from the table that the probable year of change in the pan evaporation in January month is observed between 1985 and 1992 with exception at 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 year mean was calculated to be 110.4 mm. Jagdalpur station shows increase in E_{pan} (81.8 mm) after the change year. Similarly, for the February and March month, probable change year was observed 1989 to 2001 with majority of the stations showing change in 1989-1990 (Aurangabad, Nagpur and Betul). April, May and June months also depict rise in 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 year observed between 1987 (Jagdalpur) to 2001 (Ramgundam). Jagdalpur station shows 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 having no significant change year. At Betul station, May and June months show 1997-1998 as probable year of change and remaining months recorded probable change year in 1991-1992.Probable year of change in E_{pan} at Nagpur station was observed from 1984 to 1989 and mean of sub series show decline in mean E_{pan} after the change point year.Aurangabad station shows probable year of change from 1990 to 1992 whereas June to December months does not show any significant change. Jagdalpur being the exceptional station amongst others as the month from July to December shows increased mean value of E_{pan} after the change point year, in July month mean of E_{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 9 >>>>>>>>>>>>>>>>>>>>>>>>

Pettitt's test for change detection was applied to annual values of E_{pan} as well as 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 10 shows the Pettitt test result at seasonal time-scale. Hyderabad station shows probable change year in 1992-1993 at annual, winter, pre-monsoon and post-monsoon scale whereas monsoon season shows 1989 as probable year of change. Mean of the sub-series shows uniform decreasing trend across all the seasons, annual E_{pan} value at Hyderabad shows 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 also shows change point year between the years 1987 to 1994 except for the post-monsoon season for Jagdalpur (1999) when mean of post change year is also observed higher than the previous years. Similarly Nagpur, Aurangabad and Ramgundam also shows decrease in pan evaporation value after the change point years.

<<<<<<<<<<<<<<<< Table 10 >>>>>>>>>>>>>>>>>>

Fig 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 E_{pan} trend is decreasing continuously and change in the mean is observed mostly in the decade of 90s. Jagdalpur station shows increase in mean annual evaporation after the change point year whereas Hyderabad, Betul, Nagpur shows uniform decrease in annual evaporation.

<<<<<<<<<<<<<<<<<<< Fig 5 >>>>>>>>>>>>>>>>>>

Seasonal pan evaporation series with their trend line for the sub-series of pre change point year and post change point year is shown in Figure 6. Figure shows the time-series of winter, pre-monsoon, monsoon and post-monsoon seasons with change point years. Hyderabad station shows uniform declining trend in pan evaporation 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 possess a rising trend with mean being lesser in the post shift year sub-series. Nagpur station shows shift in the series in mid of 80s 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 season whereas winter and pre-monsoon season reflect shift in mean during 1988 and 1993 respectively. Uniform shift in seasonal time-series was observed at Jagdalpur station but Ramgundam station shows no shift in pre-monsoon and monsoon season.

<<<<<<<<<<<< Fig 6 >>>>>>>>>>>>>>>>>>

4. Conclusions

Trends in the E_{pan} were investigated at annual, monthly and seasonal time scales over the Godavari basin, the largest southern peninsular river basin of India, using the non-parametric Mann-Kendall test after removing the effect of significant lag-1 serial correlation from the E_{pan} time series by using the procedure of pre-whitening. T_{max} (T_{min}) remains practically trendless at different time scales: monthly-all except December (all except July and September); and seasonal-all four seasons except post-monsoon (all the four except monsoon) over Godavari basin. Rupa Kumar et al. (1994) also reported that the warming in the Indian temperature mainly resulted from increasing temperatures up to the late 1950s, after which temperature remained nearly stable over

India. 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 basin. 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 and over six sites in annual and monsoon season over in the Godavari basin. Statistically significant decreasing (increasing) trends in wind speed (relative humidity) in pre-monsoon and in 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 by using the stepwise regression analysis. 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 may 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. Further, the tribunal awards may consider incorporating the impact of climate change into the existing agreements for the sharing of the waters of various river basins between the party states whenever the agreements are reviewed in future. 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.

5. Declaration

Funding: Not applicable.

Conflicts of interest/Competing interests: There is no conflict of interest.

Availability of data and material: Authors would like to thank India Meteorological Department for providing the meteorological data.

Code availability: Not applicable.

Authors' Contributions: All authors have contributed equally and have read it thoroughly and approve the manuscript.

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Figures

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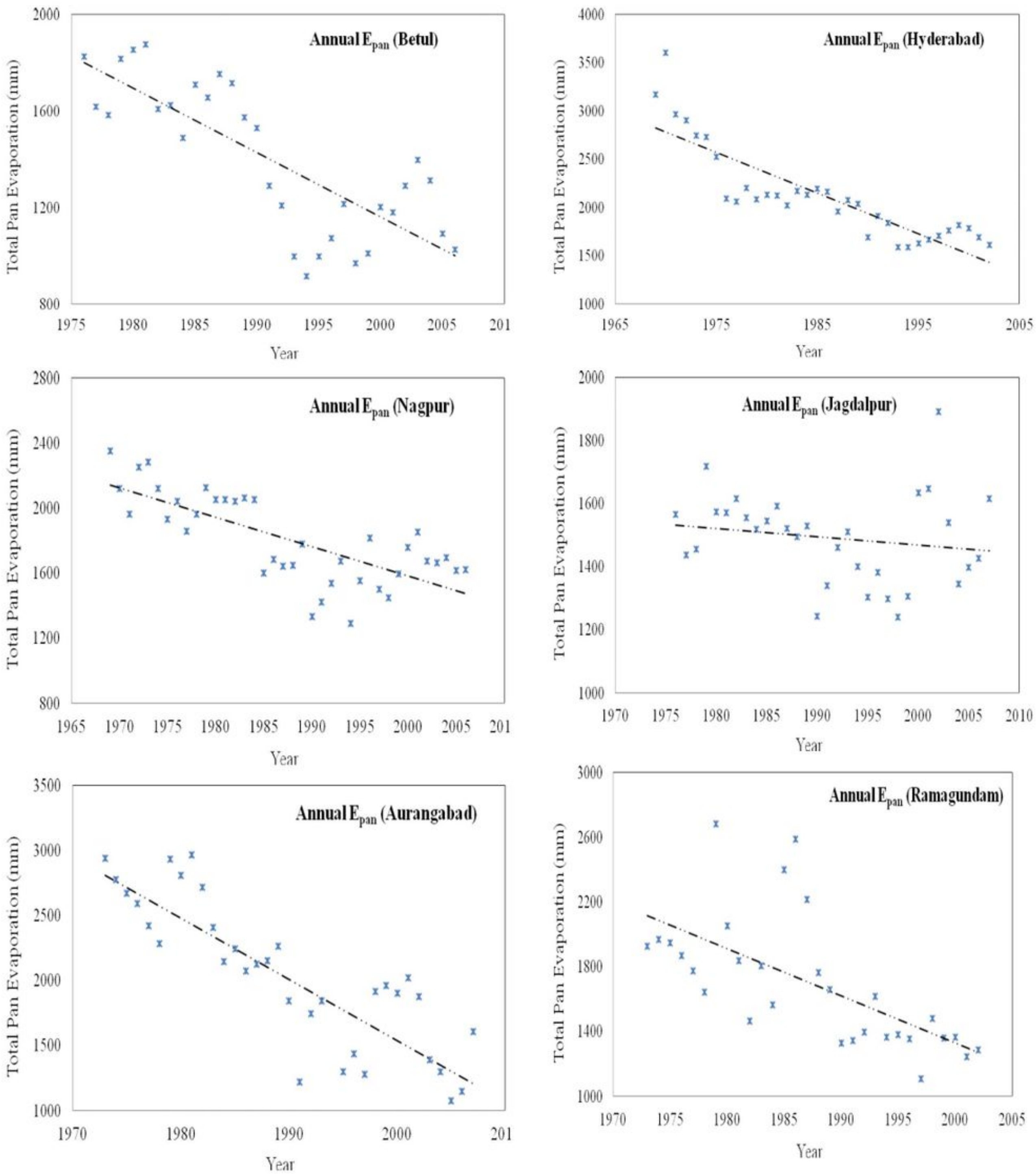

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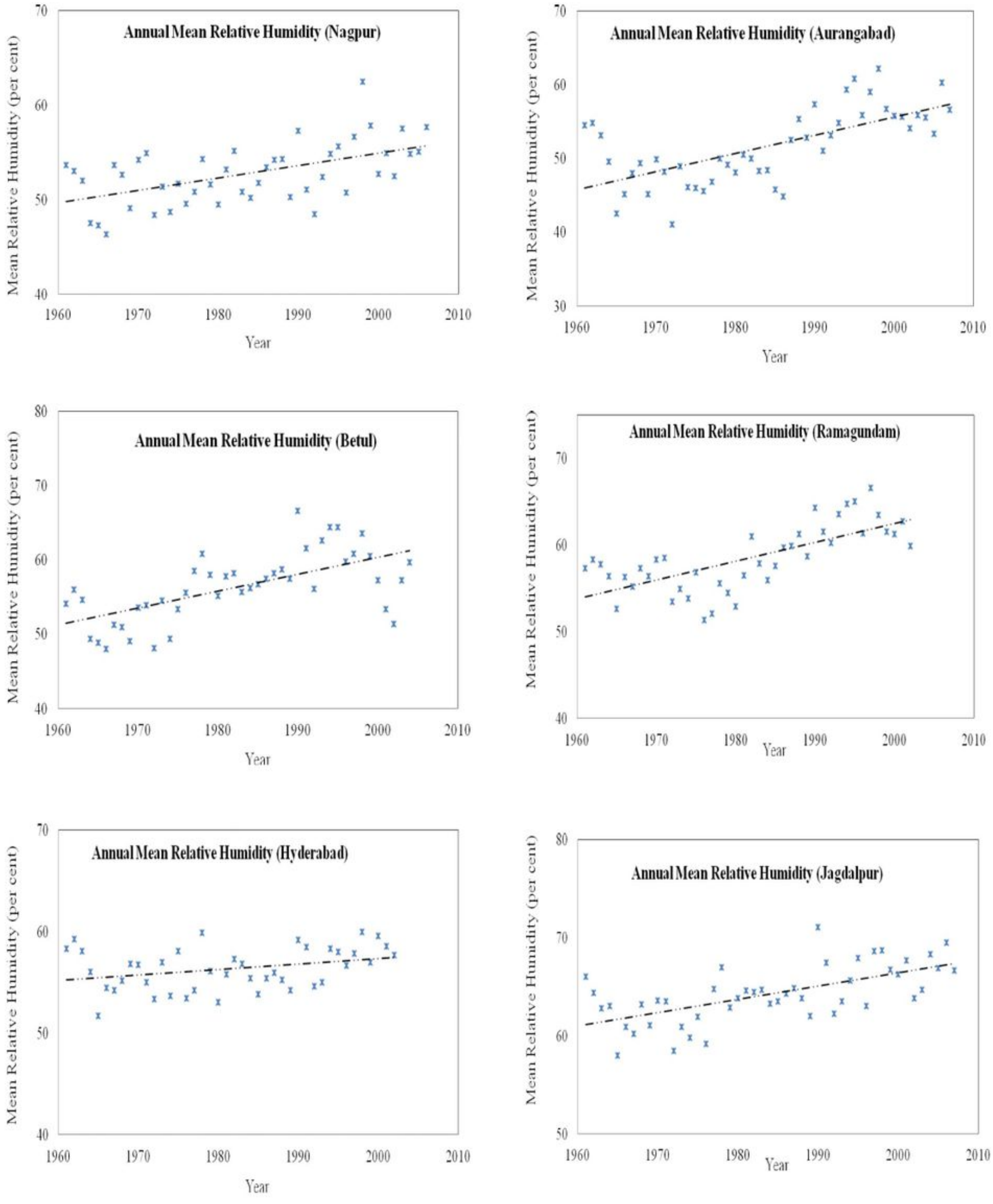

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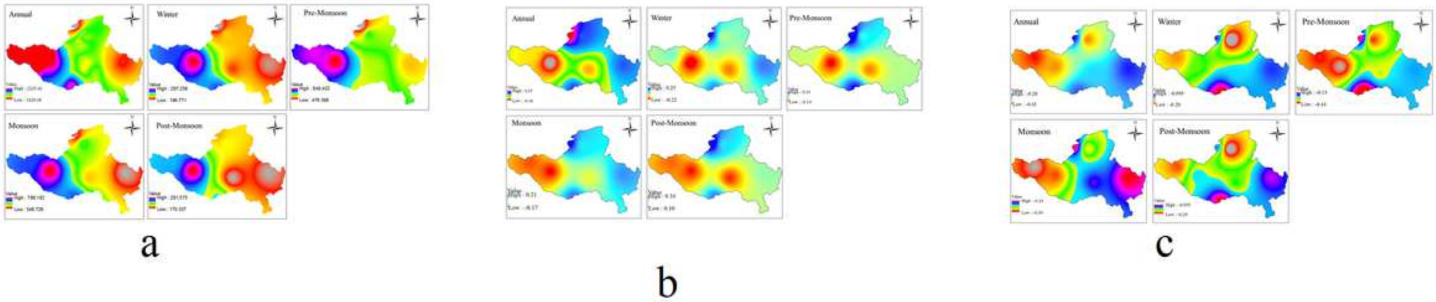

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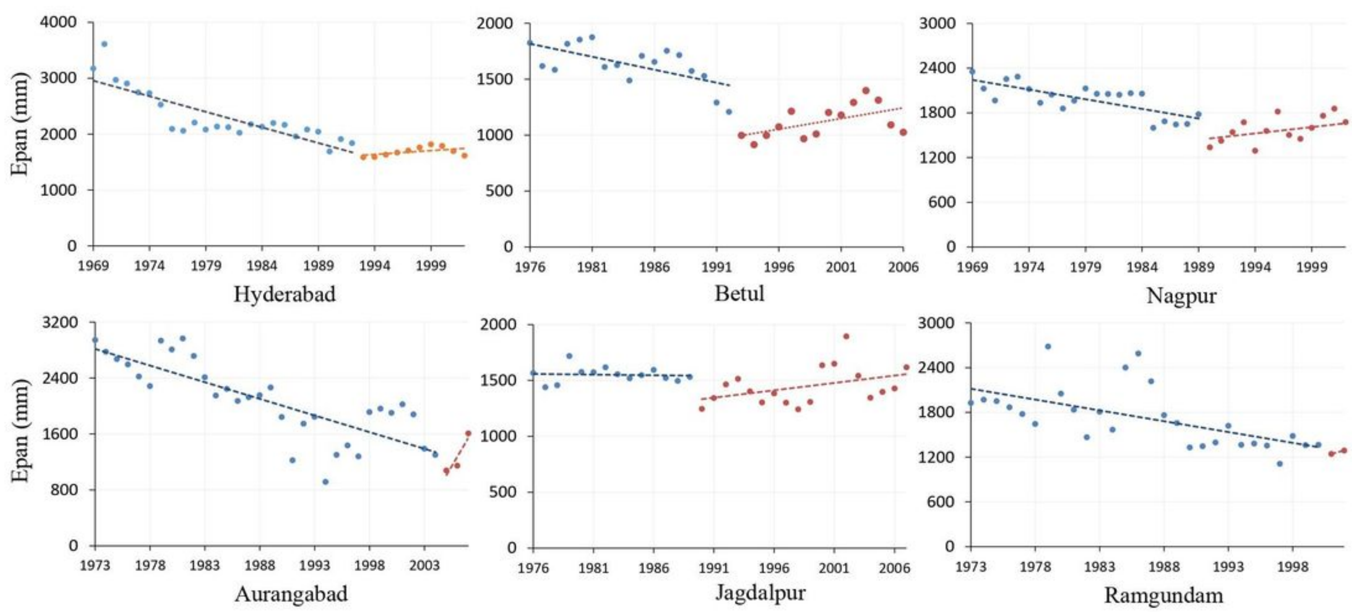

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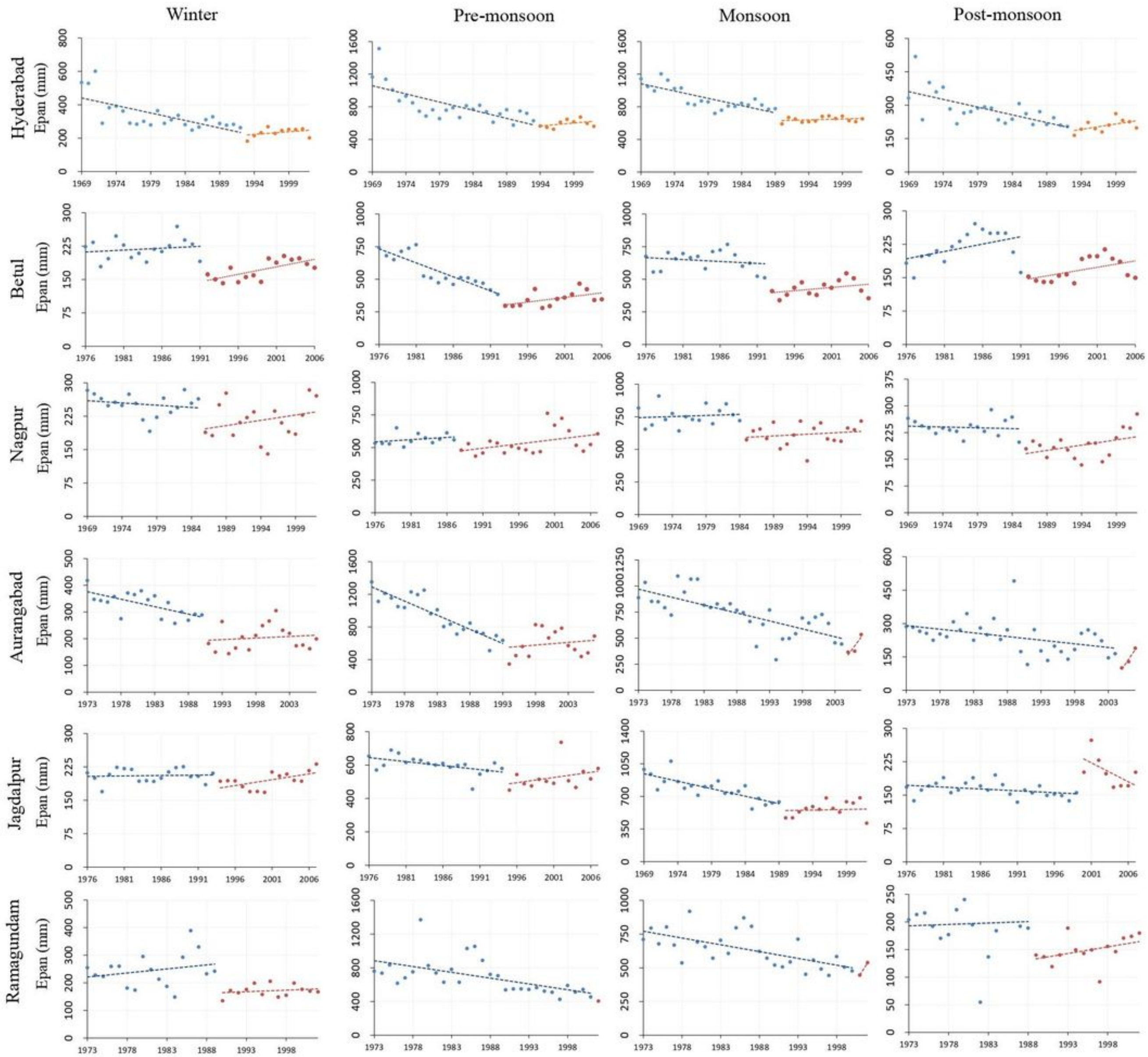

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