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Seasonal and annual variability of reference evapotranspiration at Rahuri in Semi-Arid Region of Western Maharashtra

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Abstract
Reference evapotranspiration (ET_o) serves as a critical indicator of atmospheric water demand and is essential for irrigation scheduling, crop water requirement estimation, and long-term water resource planning. This study investigates the temporal variability and trends of ET_o at Rahuri, Maharashtra, a semi-arid region of Western India, using 50 years (1975-2024) of daily meteorological data. ET_o was computed with the FAO Penman-Monteith method through the Phule Jal app, while statistical characteristics, linear trend analysis, and non-parametric Mann-Kendall (MK) test with Sen's slope estimator were employed to evaluate trends at monthly, seasonal, and annual scales. Results revealed pronounced seasonal and monthly variations, with annual mean ET_o estimated at 1683.41 mm. Summer exhibited the highest water demand (634.85 mm), while monsoon showed the lowest variability. May contributed the maximum share (14.36%) to annual ET_o, reflecting peak evaporative demand. Trend analysis indicated a highly significant long-term decline in ET_o at annual, seasonal, and monthly scales, with Sen's slope showing reductions of -12.37 mm/year (annual) and -6.96 mm/year (summer). The decline was most evident during March, April, and winter months, while some decades exhibited short-term reversals or non-significant changes, particularly in monsoon and post-monsoon periods. These findings highlight the evolving nature of atmospheric water demand in semi-arid regions and emphasize the need for adaptive irrigation and water management strategies under changing climate conditions.

Keywords: Reference evapotranspiration, statistically variability, time series analysis, Mann-Kendall, Sen's slope estimation

Introduction

Evapotranspiration (ET), as defined by the Food and Agriculture Organization (FAO), is the combined process of water loss to the atmosphere through evaporation from soil and plant surfaces and transpiration via plant leaves. To ensure consistency in estimating evapotranspiration across diverse climatic regions, FAO introduced the concept of reference evapotranspiration (ET_o)—the rate of evapotranspiration from a hypothetical reference crop characterized by a height of 0.12 m, surface resistance of 70 s/m, and an albedo of 0.23, resembling a well-watered grass surface (Allen *et al.*, 1998) [1]. ET_o serves as a critical baseline for estimating actual crop water requirements under varying agroclimatic conditions and plays a vital role in irrigation scheduling, drought monitoring, regional water allocation, and long-term water resource planning.

As ET_o is primarily governed by meteorological factors such as temperature, solar radiation, wind speed, and humidity, any long-term variation in these parameters due to climate change is expected to alter the atmospheric water demand. A standardized approach for estimating reference evapotranspiration (ET_o) is the FAO Penman-Monteith method, which integrates key climatic variables such as temperature, solar radiation, wind speed, and humidity (Allen *et al.*, 1998) [1]. It provides a consistent and reliable measure of the atmospheric water demand from a well-watered reference grass surface. Therefore, analyzing trends in ET_o provides valuable insights into shifts in regional hydrometeorological behavior and is essential for formulating adaptive strategies in agriculture and water management under changing climatic conditions.

Recent studies across varied geographical settings have reported diverse trends in ET_o and actual evapotranspiration (ET), highlighting the influence of local climatic variables. For instance, in Piazza Armerina, Sicily, a Mediterranean climate region, a significant decline in ET_o was observed in November, with specific humidity and wind speed identified as the most and least influential drivers, respectively (Aschale *et al.*, 2023) [2]. In India, several regional investigations have revealed a general decline in ET_o. The Tons River Basin in Central India showed a statistically significant downward trend, especially during the pre-monsoon and monsoon seasons, mainly attributed to declining wind speeds and rising temperatures. A 32-year nationwide study further confirmed decreasing ET_o patterns, primarily linked to increased relative humidity and reduced wind velocity (Bandyopadhyay *et al.*, 2009) [3]. Similarly, Goroshi *et al.*, (2017) [8] reported declining ET during the southwest monsoon in forested regions, whereas arid zones exhibited increasing ET due to enhanced rainfall and soil moisture availability. Contrastingly, a 45-year study over Iran indicated an increasing trend in ET_o, particularly during spring, pointing to a rising evaporative demand under warming conditions (Ghalami *et al.*, 2020) [7]. A recent analysis in the Raipur region of Chhattisgarh also recorded decreasing ET_o during peak pre-monsoon months (Kumar *et al.*, 2023) [13].

These findings underscore the complex and region-specific interactions between ET_o and climatic parameters, emphasizing the need for localized long-term assessments. To investigate the temporal dynamics of ET_o over the last five decades at Rahuri, Maharashtra—a semi-arid region of Western India—this study employed the Mann-Kendall (MK) test, a widely recognized non-parametric method for detecting trends in climatic time series. Originally developed by Mann (1945) [14] and refined by Kendall (1945) [12], the MK test is particularly suited for hydrological and meteorological data due to its robustness against non-normality and outliers. The Sen's slope estimator (Sen, 1968) [17] was used to quantify the magnitude of change per unit time. As recommended by the World Meteorological Organization (WMO), the MK test is valued for its simplicity, reliability, and suitability in long-term climate trend analysis (Bandyopadhyay *et al*., 2009) [3].

It is therefore undertaken to explore the trends in reference evapotranspiration (ET_o) at Rahuri, Maharashtra over the past 50 years, considering different time scales—weekly, monthly, seasonal, and annual—given the critical role of ET_o in agricultural planning, irrigation scheduling, and effective water resource management.

Material and Methods

Study area and Data Collected

Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri, is situated at 19.3492º N latitude and 74.6461º E longitude, with an elevation of approximately 559 meters above mean sea level (Figure 1). The daily weather data for the Rahuri region, encompassing parameters such as maximum and minimum temperature, maximum and minimum humidity, sunshine hours, and wind speed, have been recorded over a 50-year period from 1975 to 2024. The meteorological observatory is located in the Ahilyanagar district of Maharashtra, positioned on the Deccan Plateau within the rain shadow zone of the Western Ghats. Rahuri experiences a semi-arid tropical climate characterized by hot summers, moderate monsoon rainfall, and mild winters. The region receives an average annual rainfall of approximately 592 mm, predominantly during the southwest monsoon season from June to September. Temperatures range with average maximums between 30°C and 42°C, peaking in May, while minimum temperatures during December and January may fall to 8°C-10°C.

Estimation of reference evapotranspiration (ETo)

Reference crop evapotranspiration is defined as it is the rate of evapotranspiration from a reference surface. According to FAO the reference surface is a hypothetic reference crop with an assumed crop height of 0.12m, a fixed surface resistance of 70s per m^{-1} and albedo of 0.23. Various methods to compute reference crop evapotranspiration (ETo) are available in literature. The selection of particular method depends on availability of data, accuracy of data, accuracy needed in estimation and suitability of data to climatic condition. The various methods are available to estimate the reference crop evapotranspiration in the Phule Jal app developed by RKVY-IWRAS, MPKV, Rahuri. Penman-Monteith (equation 1) method as given in FAO-56 (Allen *et al*. 1998) [1] was used for computation of reference evapotranspiration (ETo) in Phule Jal app.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

Where, ETo is reference evapotranspiration (mm day^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} day^{-1}), G issoil heat flux density (MJ m^{-2} day^{-1}), Ta is mean daily air temperature (°C), u_2 is wind speed at 2 m height (m s^{-1}), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), e_s - e_a is saturation vapor pressure deficit (kPa), Δ is slope of saturation vapour pressure curve (kPa$^oC^{-1}$) and γ is psychrometric constant (kPa$^oC^{-1}$). Mean value of all six weather parameters (T_{max}, T_{min}, RH_{max}, RH_{min}, n and u_2), altitudes and latitudes were used to compute each parameter required for Penman-Monteith model.

Fig 1: Location of Rahuri in Maharashtra

Methodology

Statistical Characteristics

The universal method was used to calculate the mean, standard deviation, and coefficient of variation of reference evapotranspiration (ETo).

Linear Approach in Trend Analysis

Linear trend analysis in MS Excel involves using the TREND function, which fits a straight line to the data by applying the least squares method. To perform this, first data is organized with independent variables (years) in one column and dependent variables (ETo values) in another for considered time series. Then, apply the formula =TREND (known_y's, known_x's, new_x's, const), where known_y's are the observed data, known_x's are the corresponding time points, and new_x's represent time points for which you want predicted values. The constant (const) determines whether the intercept is forced to zero or calculated normally. After entering the formula, Excel returns predicted values along the trendline, which can be visualized alongside original data in a chart to observe increasing or decreasing trends. This method provides a straightforward approach to quantify and forecast linear trends within datasets.

Mann - Kendall non parametric test

This is a statistical method primarily used to test the null hypothesis of no trend against the alternative hypothesis of a monotonic increasing or decreasing trend in hydro-climatic time series data. For time series with fewer than 10 data points, the S-test is applied, while for more than 10 points, the normal approximation or Z-test is utilized (Gilbert, 1987). Annual, seasonal, monthly, and weekly rainfall data are evaluated as ordered time series. The Mann-Kendall Statistic (S) is calculated considering the number of tied groups (q), the number of data values in each tied group (tp), and the total number of years (n) for which data is available. The standardized test statistic Z is then computed to determine the significance of the trend. A positive or negative Z value indicates a rising or declining trend, respectively. The significance of these trends is evaluated at confidence levels of 99%, 95%, and 90%, where the null hypothesis of no trend is rejected if |Z| > 2.575, |Z| > 1.96, and |Z| > 1.645, respectively. Following the equations involved in evaluation of trend using Mann-Kendall method.

The following equations (2, 3, 4 and 5) are used in the evaluation of trends using the Mann-Kendall method:

The Mann-Kendall statistic *S* is calculated as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign(X_j - X_k) \quad (2)$$

Where *n* is the number of data points, xi and *xj* are individual data values with *j*>*i*, and the sign function *sign* is defined as:

$$sign(X_j - X_k) = \begin{cases} 1 & if \quad (X_j - X_k) > 0 \\ 0 & if \quad (X_j - X_k) = 0 \\ -1 & if \quad (X_j - X_k) < 0 \end{cases} \quad (3)$$

The variance of *VAR(S)*, accounting for tied groups, is given by

$$VAR(S) = \frac{1}{16}\left[n(n-1)(2n+5) - \sum_{p+1}^{q} t_p(t_p - 1)(2t_p + 5) \right] \quad (4)$$

Where *q* is the number of tied groups and *tp* is the number of data points in the p^{th} tied group. The standardized test statistic *Z* is computed as:

$$Z = \begin{cases} \frac{s-1}{\sqrt{VAR(S)}} & if\ S > o \\ 0 & if\ S > o \\ \frac{s+1}{\sqrt{VAR(S)}} & if\ S > o \end{cases} \quad (5)$$

This Z-value follows a standard normal distribution and is used to evaluate the presence of a statistically significant monotonic trend in the data.

Sen's Slope Estimation

To estimate the true slope of an existing linear trend, Sen's non-parametric method (Equation 6 and 7) is used. This method calculates the slope Q_i for all pairs of observations in a time series as:

$$Q_i = \frac{x_i - x_k}{j - k} \quad (6)$$

Where x_j and x_k are data values at times j and k respectively, and $j>k$. If there are n data points, the total number of slope estimates N is $n(n-1)/2$. The Sen's slope estimator Q_t, representing the magnitude of the trend, is the median of these NN slope values. The estimator is computed as:

$$Q_t = \begin{cases} Q_{\frac{N+1}{2}} & if\ N\ is\ odd \\ \frac{1}{2}\left(Q_N + Q_{\frac{N+1}{2}}\right) & if\ N\ is\ even \end{cases} \quad (7)$$

A positive Q_t indicates an increasing trend, whereas a negative Q_t indicates a decreasing trend. The Sen's slope is typically calculated for series where the Mann-Kendall test has identified a statistically significant trend.

Results and Discussion

Statistical Characteristics and Interannual Variability

The reference evapotranspiration (ETo) data spanning 50 years from 1975 to 2024 at Rahuri exhibits clear seasonal and monthly variations, with its statistical characteristics summarized in Table 1. On an annual scale, the mean ETo was 1683.41 mm, accompanied by a standard deviation of 194.44 mm and a coefficient of variation (CV) of 11.55%, indicating moderate variability in atmospheric water demand.

Seasonal analysis shows that the summer season recorded the highest average ETo at 634.85 mm, with the greatest variability (CV = 17.80%), reflecting the high evaporative demand and climatic fluctuations typical of this period. In contrast, the monsoon season exhibited the lowest variability (CV = 7.33%), suggesting more stable evapotranspiration under relatively uniform weather conditions.

At the monthly scale, May recorded the highest mean ETo (241.67 mm), followed by April and March, while December had the lowest (91.26 mm). Notably, March and April exhibited the highest monthly variability with CVs of 21.47% and 20.81%, respectively, highlighting significant interannual fluctuations in evapotranspiration during the pre-monsoon months.

Table 1: Statistical characteristics of Reference Evapotranspiration (ETo) at Rahuri during 1975 - 2024.

Time Series	Mean (mm)	SD (mm)	CV (%)
Annual	1683.41	194.44	11.55
Summer	634.85	112.99	17.80
Monsoon	514.95	37.76	7.33
Post Monsoon	223.87	28.32	12.65
Winter	309.75	47.38	15.30
January	99.33	16.66	16.77
February	119.16	21.25	17.84
March	176.02	37.80	21.47
April	217.16	45.19	20.81
May	241.67	37.83	15.66
June	160.15	21.02	13.13
July	121.35	14.25	11.74
August	117.19	10.13	8.64
September	116.25	12.89	11.08
October	122.98	18.00	14.63
November	100.89	12.35	12.24
December	91.26	13.49	14.78

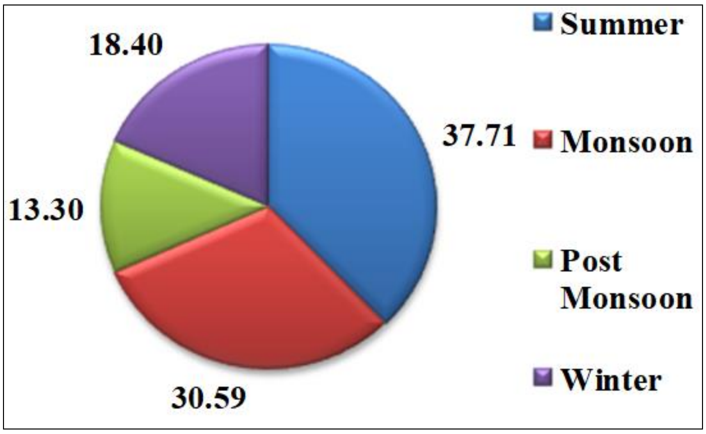

Fig 2: Contribution (%) of average seasonal ETo to average annual ETo during last 50 years (1975 - 2024)

The average seasonal contribution to average annual ETo, as illustrated in Figure 2, further emphasizes the dominance of the summer and monsoon periods. Summer accounts for the largest share at 37.71%, followed by the monsoon season at 30.59%. Winter and post-monsoon seasons contribute 18.40% and 13.30%, respectively. This distribution reflects higher atmospheric water demand during the warmer parts of the year.

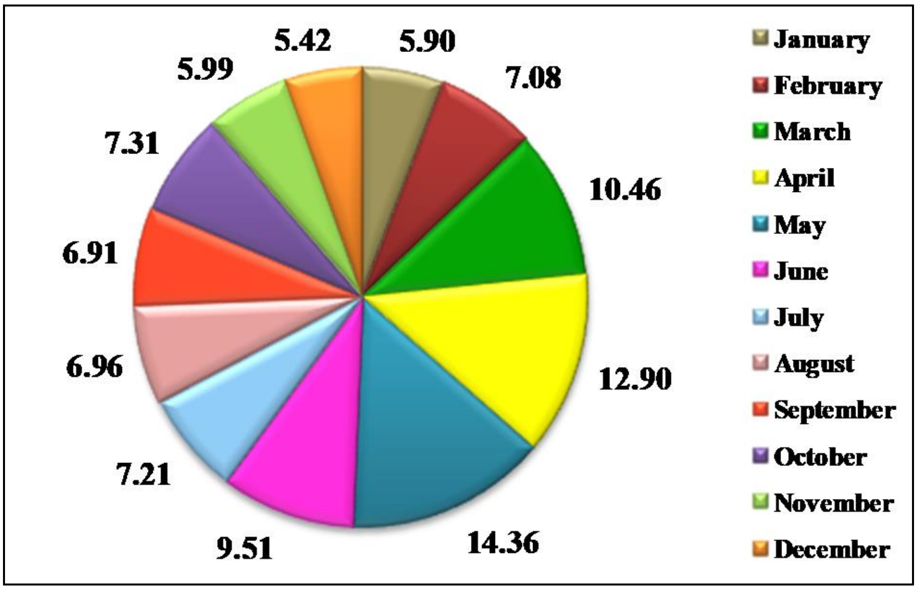

Fig 3: Contribution (%) of average monthly ETo to average annual ETo during last 50 years (1975 - 2024)

Figure 3, showing average monthly contributions to average annual ETo, aligns with this trend. May contributes the most at 14.36%, followed by April (12.90%) and March (10.46%), underscoring peak evapotranspiration in the pre-monsoon summer months. Moderate contributions from June (9.51%), July (7.21%), and August (7.31%) correspond to the monsoon period, while the lowest contributions are observed in January (5.42%) and December (5.90%), aligning with the cooler winter months. These patterns collectively highlight a strong seasonal variation in ETo, with higher values during hot months and significantly lower values during cooler periods, emphasizing the need for season-specific water management strategies.

Analysis of trends through a linear trendline approach

Figure 4 displays the annual reference evapotranspiration (ETo) trends using a linear trendline approach for the overall period (1975-2024) and each individual decade. The overall trend (Figure 4a) shows a significant decline in annual ETo, indicating a long-term reduction in atmospheric evaporative demand. Decadal trends (Figures 4b-f) reveal variations—while 1985-1994 and 2015-2024 show a clear decreasing trend, the period 2005-2014 reflects a slight upward trend, and the other decades remain relatively stable. These patterns suggest both short-term fluctuations and a broader declining trend likely influenced by climatic shifts.

Figure 5 presents seasonal ETo trends over the 50-year period for Summer, Monsoon, Post-Monsoon, and Winter seasons. The Summer and Winter seasons exhibit distinct declining trends, pointing to a consistent reduction in evaporative demand during temperature extremes. The Monsoon season shows a slightly negative trend, likely due to high humidity and cloud cover, while the Post-Monsoon period remains largely stable. These seasonal trends emphasize the need to reassess water resource planning and crop irrigation strategies under changing climatic conditions.

Results of Trend analysis using Mann -Kendall and Sens slope estimator method

The trend analysis results of reference evapotranspiration (ETo) for the period 1975 to 2024, including sub-decadal intervals, were evaluated using the Mann-Kendall Test (Z) and Sen's Slope (Q, in mm/year). Table 2 presents the trends observed in the annual and seasonal time series (summer, monsoon, post-monsoon, and winter), while Table 3 shows the trends in the monthly time series over the same period.

During the 50-year period (1975-2024), a highly significant decreasing trend (99% level) was observed in annual, summer, post-monsoon, and winter ETo, with Z-values ranging from -6.71 to -7.73 and Sen's slopes indicating substantial reductions, especially in annual (-12.37 mm/year) and summer (-6.96 mm/year) series. The monsoon season showed a moderately significant decreasing trend (at 95% level) with a Z-value of -2.71 and a slope of -1.08 mm/year. These results collectively indicate a consistent and significant decline in reference evapotranspiration across all seasons, with varying degrees of statistical confidence. During 1975 and 1984, no significant trend was observed in any of the seasonal or annual ETo time series. The Mann-Kendall Z values for all considered time series (annual and seasonal) remained negative but statistically non-significant, indicating a climatologically stable period without notable changes in evaporative demand. The decade from 1985 to 1994 marked the beginning of a significant decline in ETo. A statistically significant decreasing trend was observed in the Annual, Summer, Post-Monsoon (95% confidence) and Winter (99% confidence) time series. This suggests a climatic shift with reduced evaporative demand, possibly due to changes in climatic parameters. No significant trends were recorded during 1995 to 2004 across any time series. ETo values showed slight positive slopes in some seasons, but they were statistically non-significant. This decade can be viewed as a transitional phase, reflecting short-term variability rather than long-term climatic patterns.

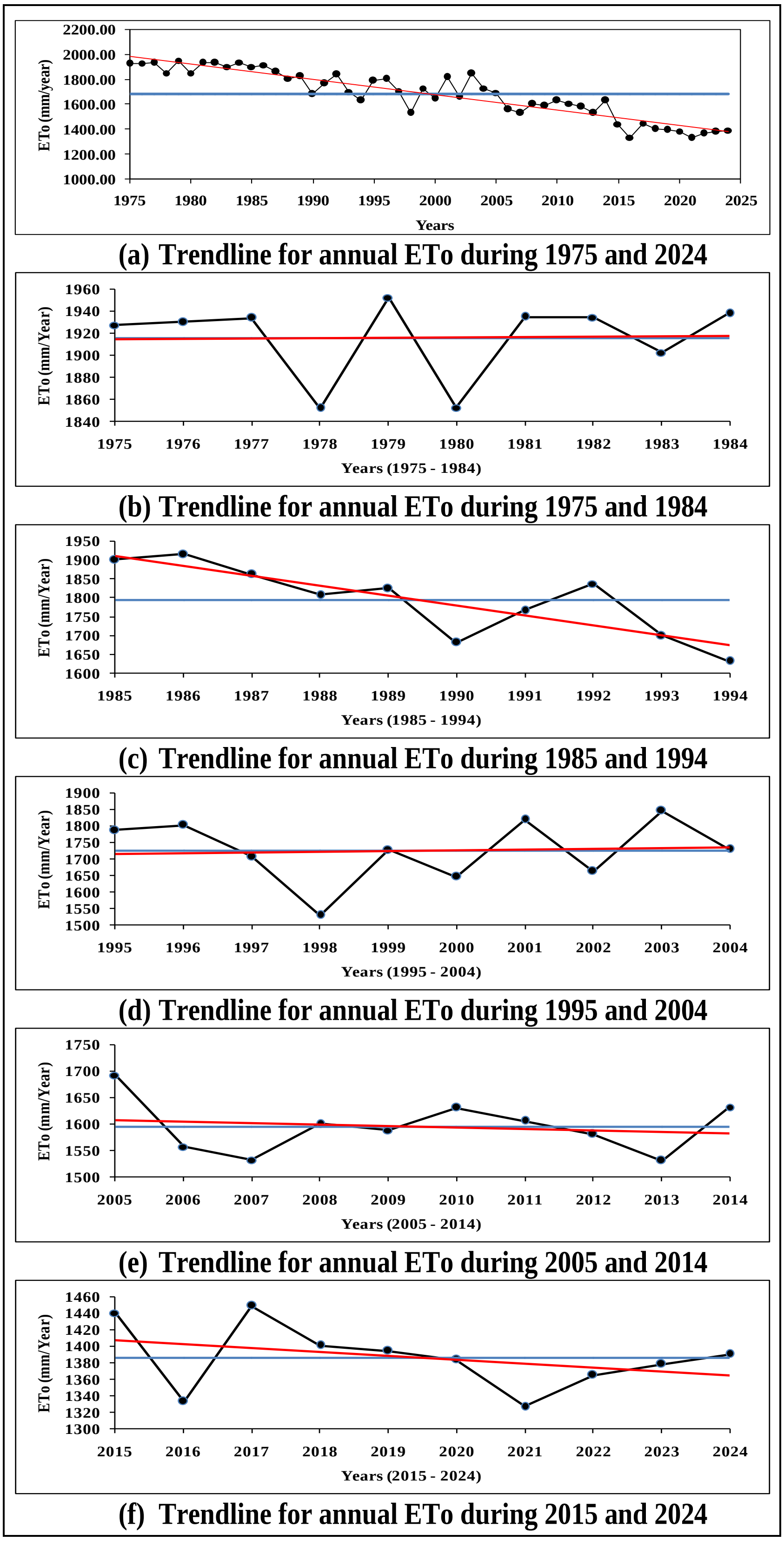

Fig 4: Annual ETo trends based on linear trendlines for the overall period (a) and individual decades (b to f)

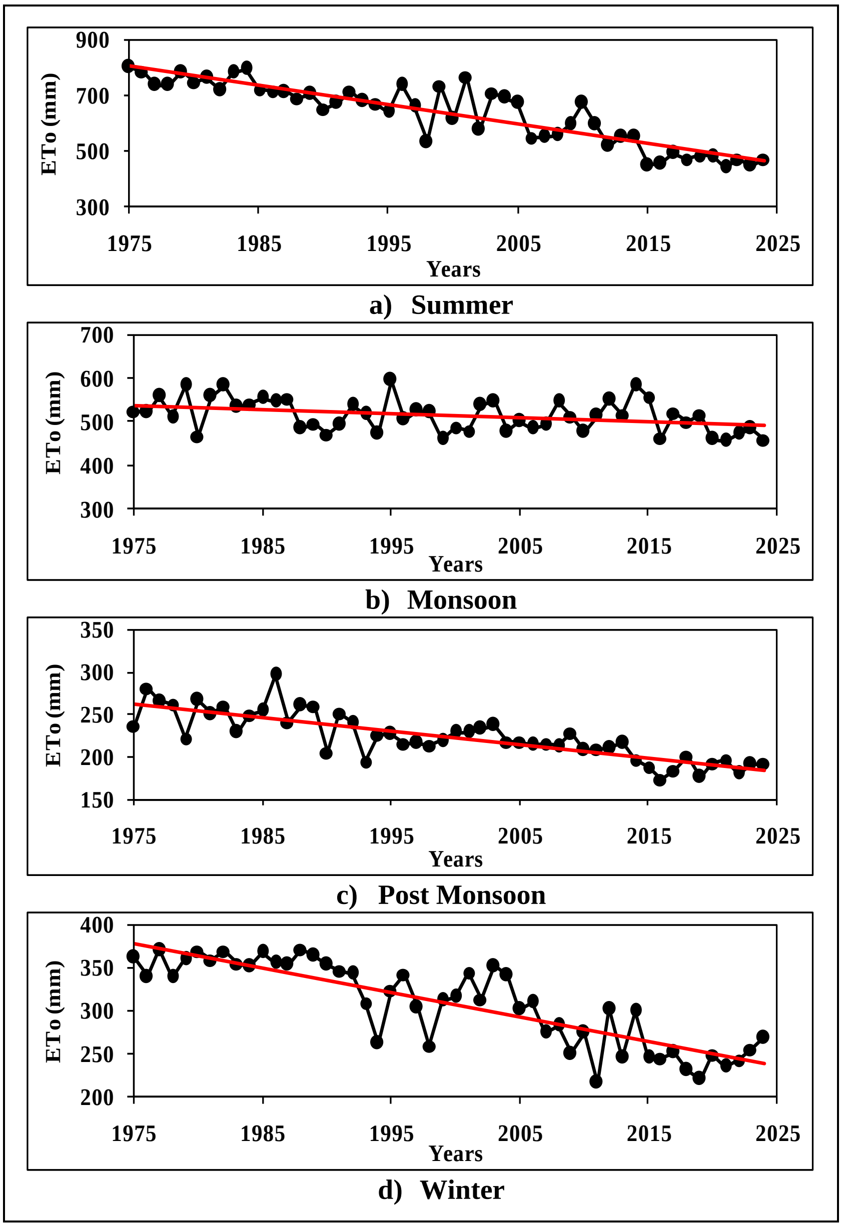

Fig 5: Seasonal ETo trends based on linear trendlines for the overall period

During 2005 and 2014 significant increasing trend was observed in the Monsoon ETo time series (90% confidence). All other time series remained non-significant. This suggests a rise in evaporative demand during the monsoon, likely linked to higher temperatures or reduced relative humidity during this period. The post-monsoon period during 2015 and 2024 showed a significantly decreasing trend (90% confidence), while all other time series did not exhibit statistically significant changes. This suggests a renewed decline in ETo, particularly after the rainy season, reflecting potential shifts in weather patterns or reduced solar inputs.

During the overall 50-year period, a strong and consistent decreasing trend in ETo is observed in most months. January through May and September through December exhibit highly significant (99%) declines, with the steepest drop seen in March (Z = -7.14). July also shows a significant decline at the 95% level, while June and August are non-significant. This suggests a widespread, long-term reduction in evaporative demand across nearly the entire year. In this initial decade (1975-1984), no significant trends were observed across any of the months. Monthly Z-values remain within the non-significant range, indicating stability in ETo patterns during this period. This phase can be considered a baseline against which subsequent climatic shifts may be compared, with no major alterations in atmospheric evaporative demand during this time. The decade from 1985 to 1994 marks the beginning of statistically significant declines in ETo. February and November show moderate (95%) decreasing trends, while April and August show weakly significant (90%) decreases. The rest of the months remain non-significant. This indicates that ETo decline began to emerge, especially in late winter, summer, and post-monsoon months, reflecting possible impacts of early climate change signals or shifts in regional weather patterns. The decade from 1095 to 2004 shows limited and isolated increasing trends. Only January recorded a significant increasing trend at the 90% level, while all other months were non-significant. The increase in ETo during January could be due to rising minimum temperatures or clearer skies in winter. Overall, this period appears to represent a temporary pause or reversal in the declining trend observed in the previous decade. In this period 2005 to 2014, only September showed a significant increasing trend at the 95% level, with all other months being non-significant. The increase in September may reflect a localized climatic anomaly or short-term variability during the late monsoon season. The rest of the months exhibited no statistically relevant change, indicating a relatively stable ETo pattern throughout the year during this decade. The most recent decade from 2015 to 2024 shows mixed and weakly significant monthly trends. January exhibited a slight increasing trend (90% level), possibly linked to winter warming, whereas August showed a weakly significant decrease. All other months remained statistically non-significant. This indicates that recent changes in ETo are not uniformly directional and are likely influenced by short-term variability rather than long-term climatic trends.

Table 2: Trends observed in the annual and seasonal time series (summer, monsoon, post-monsoon, and winter)

Duration	Parameter	Time Series				
		Annual	Summer	Monsoon	Post Monsoon	Winter
1975-2024	Test Z	-7.73	-7.39	-2.71	-6.71	-6.98
	Signific.	***	***	***	***	***
	Q (mm/year)	-12.37	-6.96	-1.08	-1.62	-2.80
1975-1984	Test Z	0.89	-0.18	0.36	-1.07	-0.54
	Signific.	-	-	-	-	-
	Q (mm/year)	0.91	-0.42	1.70	-3.43	-0.41
1985-1994	Test Z	-2.50	-2.15	-1.61	-2.15	-3.04
	Signific.	**	**	-	**	***
	Q (mm/year)	-29.32	-5.505	-5.993	-6.710	-7.080
1995-2004	Test Z	0.36	0.00	-0.72	1.61	1.07
	Signific.	-	-	-	-	-
	Q (mm/year)	3.14	4.519	-4.438	1.270	3.560
2005-2014	Test Z	0.00	-0.54	1.97	-1.43	-0.54
	Signific.	-	-	**	-	-
	Q (mm/year)	-0.17	-1.480	6.500	-1.277	-1.300
2015-2024	Test Z	-1.25	0.00	-1.79	0.89	0.89
	Signific.	-	-	*	-	-
	Q (mm/year)	-6.45	-0.299	-7.050	1.120	1.474

Note:
1. Significance levels for Mann-Kendall Test: (i) non-significant: $|Z| < 1.64$ (-), (ii) 90%: $1.64 \le |Z| \le 1.96$ (*), (iii) 95%: $1.96 < |Z| \le 2.54$ (**), (iv) 99%: $|Z| > 2.54$ (***).
2. - ve sign indicate decreasing trend

Table 3: Trends in the monthly time series during 1975 and 2024

Duration	Parameter	Time Series											
		Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1975-2024	Test Z	-5.76	-6.34	-7.14	-6.91	-5.96	-1.12	-2.09	-0.10	-4.02	-6.14	-6.12	-5.91
	Signific.	***	***	***	***	***	-	**	-	***	***	***	***
	Q (mm/year)	-0.88	-1.24	-2.27	-2.65	-2.04	-0.24	-0.27	-0.02	-0.53	-0.92	-0.69	-0.71
1975-1984	Test Z	0.18	0.00	0.36	-0.89	0.54	0.89	0.36	1.07	-0.54	-0.72	0.00	0.00
	Signific.	-	-	-	-	-	-	-	-	-	-	-	-
	Q (mm/year)	0.23	-0.27	0.38	-1.44	1.77	1.82	0.86	1.40	-1.24	-2.46	-0.14	-0.51
1985-1994	Test Z	-1.43	-1.97	-0.18	-1.79	0.00	0.36	-1.07	-1.79	-1.61	-1.43	-2.50	-1.61
	Signific.	-	**	-	*	-	-	-	*	-	-	**	-
	Q (mm/year)	-1.50	-2.05	-0.43	-3.98	0.15	0.75	-2.47	-2.44	-2.56	-2.47	-3.05	-1.18
1995-2004	Test Z	1.79	0.54	0.54	0.18	0.00	-1.07	1.07	-0.72	-0.72	0.89	0.36	1.25
	Signific.	*	-	-	-	-	-	-	-	-	-	-	-
	Q (mm/year)	1.88	0.71	2.39	0.68	0.32	-5.01	0.73	-1.51	-0.54	0.78	0.33	1.15
2005-2014	Test Z	0.72	-1.07	-1.25	-0.18	-0.89	1.07	1.07	1.07	2.15	-1.07	-0.18	-0.54
	Signific.	-	-	-	-	-	-	-	-	**	-	-	-
	Q (mm/year)	0.81	-1.03	-2.55	-2.83	-1.75	3.92	1.01	1.45	1.71	-0.99	-0.23	-0.96
2015-2024	Test Z	1.79	-0.54	0.72	-0.36	-0.18	-0.54	-1.79	-0.89	-0.18	0.36	0.36	1.07
	Signific.	*	-	-	-	-	-	*	-	-	-	-	-
	Q (mm/year)	0.96	-0.07	0.68	-0.07	-0.53	-0.76	-4.86	-1.61	-0.30	0.54	0.27	0.80

Note -
1. Significance levels for Mann-Kendall Test: (i) non-significant: $|Z| < 1.64$ (-), (ii) 90%: $1.64 \le |Z| \le 1.96$ (*), (iii) 95%: $1.96 < |Z| \le 2.54$ (**), (iv) 99%: $|Z| > 2.54$ (***).
2. - ve sign indicate decreasing trend

Discussion

The observed and statistically validated decline in ETo at Rahuri parallels findings from multiple regions across India, where significant downward trends have been consistently detected via robust non-parametric tests, such as Mann-Kendall and Sen's slope. This decreasing trend in reference evapotranspiration aligns with the literature, which reports similar patterns in diverse agro-ecological zones, including the humid northeast (Jhajharia *et al.*, 2011) [10], arid and semi-arid northwest India (Saxena *et al.*, 2020) [16], and districts like Ludhiana in Punjab (Kaur & Kaur, 2022) [11]. Notably, exceptions exist, such as the Narmada River basin (Pandey & Khare, 2018) [15], which featured a positive annual trend, emphasizing regional heterogeneity and the influence of localized hydro-climatic factors The primary meteorological drivers responsible for this decline are reductions in net radiation, decreased wind speed, and fewer sunshine hours, all of which counterbalance the effect of rising temperatures—an outcome corroborated by studies in Udaipur (Jalgaonkar *et al.*, 2017) [9] and other regions. Increasing humidity further enhances the downward trend in ETo, while changes in rainfall patterns contribute regionally specific responses From an agricultural perspective, declining ETo suggests reduced irrigation requirements, potentially enabling improved water management and crop system intensification, particularly in water-limited environments. However, decadal and monthly analyses reveal episodes of variability, with some decades (e.g., 2005-2014) and months (e.g., September, January in some sub-periods) showing short-term reversals or non-significant changes, likely reflecting transient climatic fluctuations or anomalies. Moreover, while current ETo trends indicate a reduction in crop water demand, climate projections caution that potential evapotranspiration may rise under future warming scenarios, with impacts varying spatially and seasonally (Chattopadhyay & Hulme, 1997) [4]. This possibility necessitates continued monitoring of ETo alongside temperature and rainfall trends, as water management and agricultural productivity could be challenged if rainfall increases do not offset heightened evaporative losses. In summary, the analysis of Rahuri ETo trends demonstrates a statistically significant, seasonally widespread decline over the last five decades, echoing national patterns and suggesting that ongoing climatic changes are actively reshaping atmospheric water demand. These insights underscore the importance of adaptive water resource management strategies attuned to both long-term climate signals and short-term variability.

Conclusion

The observed results show that reference evapotranspiration (ETo) at Rahuri over the 50-year period exhibits clear seasonal and monthly variations, with an overall significant declining trend in annual and seasonal ETo, particularly in summer and winter periods. High water demand during summer months is evident from the higher ETo values and greater variability, while the monsoon season shows lower and more stable evapotranspiration. The dominant contribution of summer and monsoon to the annual ETo aligns with expected climatic patterns of high temperatures and rainfall cycles. Trend analyses using Mann-Kendall and Sen’s slope estimators confirm a highly significant decrease in ETo at annual and seasonal scales, consistent with similar findings across various Indian agro-ecological regions. The decline in reference evapotranspiration (ETo) may be attributed to changes in climatic variables which counterbalance the effect of rising temperatures. However, further studies are needed to comprehensively confirm and quantify the individual impacts of different climatic factors on ETo variations. Shorter-term variations, including periods of stability and minor increases in some decades, reflect climatic fluctuations. These patterns highlight the evolving nature of atmospheric water demand and underscore the critical need for further detailed studies to better understand the driving factors and future behaviour of reference evapotranspiration under changing climate conditions. Continued and comprehensive research is essential to accurately quantify the influences of various climatic variables on ETo trends and to anticipate potential shifts due to ongoing climate change.

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