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RESEARCH ARTICLE

Assessing reference evapotranspiration trends in the Amaravathi river basin

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Abstract

Evapotranspiration (ET) is a key component of the hydrological cycle and climate change has impacted its patterns, potentially leading to abnormal weather conditions. This study investigates the trends in reference evapotranspiration (ET_0) over the Amaravathi river basin using monthly ET_0 of AgERA5 dataset from 1979 to 2022. The result revealed that the mean annual ET_0 was 1909.79 mm with a low coefficient of variation (CV) of 3.14 %, indicating stability despite seasonal fluctuations. The Southwest Monsoon (SWM) accounted for the largest share (36.20 %) of annual ET_0, followed by summer (30.30 %), Northeast Monsoon (NEM) (18.48 %) and winter (15.02 %). Trend analysis using the Mann-Kendall test and Sen's slope estimation showed a significant decreasing trend in annual ET_0 at a rate of 2.35 mm per year ($p < 0.05$), suggesting a long-term decline in evapotranspiration potential. Pettitt's test identified a significant change point in the ET_0 series, with a shift around 2003, indicating a change in the climatic regime. Principal Component Analysis (PCA) further corroborated these trends, with the first principal component (PC1) explaining 63.24 % of the variance, strongly correlating with ET_0, solar radiation and mean temperature. The significant drop in ET_0 over the previous few decades is highlighted in this study, highlighting the necessity of adaptive water management techniques considering shifting climatic conditions.

Keywords: climate variability; evapotranspiration; Mann-Kendall test; river basin; trend analysis

Introduction

Recent confirmation of climate change driven by anthropogenic activities has resulted in increased atmospheric CO_2 levels and other radiatively active gases. It amplifies the greenhouse effect and elevates global temperature has a substantial impact on global food production. Various studies have reported decreased precipitation and enhanced evaporation demand in different regions due to global warming resulting in surface aridity and extreme droughts in the twenty-first century (1). Increasing level of CO_2, air temperature and high vapour pressure deficit (VPD), followed by radiation transfer alters both biotic and abiotic processes governing evapotranspiration (ET) (2). Climate change largely influences meteorological variables which eventually increase the evapotranspiration rates and cause dry conditions which aggravate desertification (3). ET is a key variable linking ecosystems, the water cycle and carbon sources. Its application has shown significant enhancement across a wide array of fields over the last decades (4).

Evapotranspiration is a vital component of the hydrological cycle as it influences ecological systems energy budget and water balance. The term evapotranspiration represents both evaporation pathways from open water bodies and transpiration which occurs from stomata to the atmosphere of (5). Since agriculture uses a significant amount of the available water resources, accurate estimation of its water consumption is crucial for sustainable water management. This can be achieved by integrating advanced technological approaches, particularly remote sensing technology and machine learning approaches, which offers precise agricultural water management (6). The accurate assessment of evapotranspiration at higher spatial and temporal resolution has critical role in developing water management strategies at regional level. It enables to identify the high evaporative demand regions, which helps in making decisions on land use planning, water management and identifying and managing drought conditions (7). The differences in evapotranspiration's geographical distribution are still quite unclear. Due to observation record constraints, particularly in semiarid locations with underdeveloped economic systems and scant data, it is unclear how evapotranspiration rates have changed over time in various places (8). The measurement of evapotranspiration from a reference surface (grass) under present weather conditions, with no restrictions on water availability, is known as reference evapotranspiration (ET_0).

Typical techniques for calculating reference evapotranspiration include Penman-Monteith, radiation, pan evaporation and Blaney-Criddle (9). Numerous remote sensing (RS) methods have been developed to estimate spatial evapotranspiration. The Simplified Surface Energy Balance Index, Surface Energy Balance System, Surface Energy Balance Algorithm for Land (SEBAL) and Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC) are important models of evapotranspiration that are based on remote sensing. The accurate assessment of models can be ensured by estimating the eddy covariance and Penman-Monteith (PM) models (10). Among numerous methods for estimating reference evapotranspiration, the Penman-Monteith FAO56 (ET_{pmf}) method has been recommended as a standardized and reliable model across diverse sites and climatic conditions (11).

Globally several studies have assessed ET trends reporting both increasing and decreasing trends (13-15). Few studies have reported increasing trends (16-18) and downward trends in several countries worldwide (19-22). Evapotranspiration (ET) has been decreasing across India at a proportion of 0.22 mm per year, with forests showing the most significant decline at 1.75 mm per year. However, a downward trend was noted during the drought, the effects of El Niño and monsoon fluctuations and increasing temperature differences (0.64°C per decade) are associated with rising ET trends in certain regions (23, 24). Tamil Nadu's trend study reveals a mixed environment, with certain components rising while others fall. Evapotranspiration has dropped despite rising temperatures, a phenomenon known as the evaporation paradox, according to 23-year research conducted in the Lower Bhavani Basin (25) In addition, multiple researchers have documented both upward and downward ET_0 trends in regions with varying climate conditions (26).

This study captures the variation in ET under various agricultural situations by analysing its dynamics within a particular region with a variety of cropping patterns. Future studies on water productivity will be built upon the knowledge acquired, emphasizing the significance of effective irrigation techniques in maximizing water usage efficiency and advancing sustainable agriculture.

Material and Methods

Study area

The Amaravathi River basin, situated in western Tamil Nadu (Fig. 1) spans across 8280 square kilometres, covering parts of Coimbatore, Tiruppur, Dindigul and Karur districts. This diverse terrain supports a mosaic of ecosystems, including forests, agricultural lands, human settlements and water bodies, all of which interact to shape the region's water resources. The basin experiences a semi-arid climate, rendering it highly vulnerable to climate fluctuations. Consequently, it serves as an excellent location for investigating the impact of climate change on reference evapotranspiration, a crucial parameter in hydrological studies. Despite moderate to high rainfall (1029 mm annually), high evapotranspiration rates significantly affect the hydrological cycle. This study examines the dynamics of reference evapotranspiration (ET_0), a critical climatic parameter sensitive to temperature and radiation changes. Understanding ET_0 spatial and temporal variability is vital for assessing water availability, optimizing irrigation and developing resilient water management strategies under changing climate conditions.

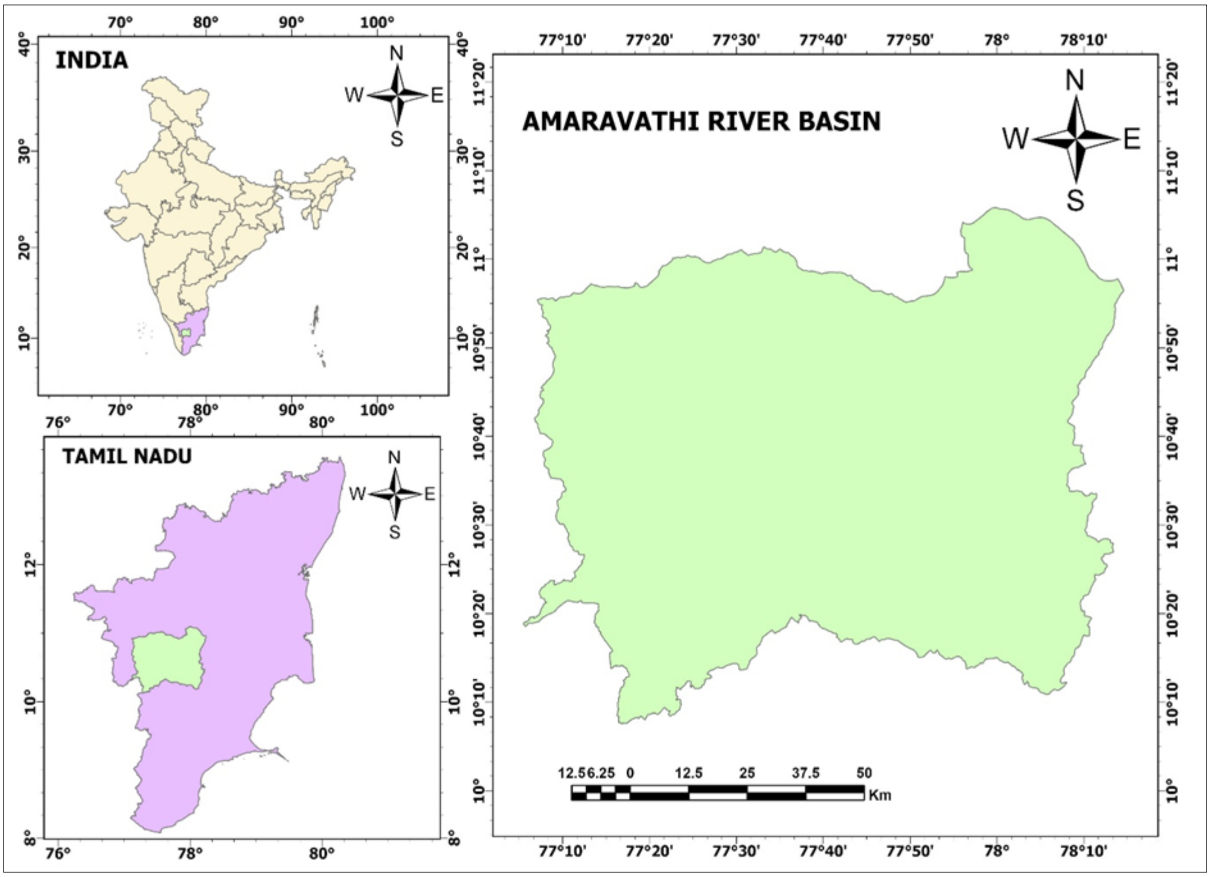


Fig. 1. Location map of the study area.

Data sources

The study utilizes daily reference evapotranspiration from the United Nations Food and Agriculture Organization (FAO) with a spatial resolution of 0.1° (approx.). The meteorological variables from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) dataset was used by FAO to compute reference evapotranspiration. The AQUASTAT Climate Information Tool (https://aquastat.fao.org/climate-information-tool/) was used to get reference evapotranspiration (ET_0) data for study region, which comprises 101 grids, based on FAO-56 Penman-Monteith (PM) method. A comprehensive framework for assessing for variability and trends of ET_0 in the basin was provided by the retrieval of the monthly ET_0 over a 43 year period (1979-2022).

The FAO-56 method was utilized to adjust wind speed to a standard height of 2 meters, ensuring consistency in reference evapotranspiration (ET_0) calculations. The AQUASTAT tool was employed to process wind speed data from the KNERA dataset, aligning with FAO guidelines for accurate application. AgERA 5 data validated with ground truth data (27). This standardization enhances the precision of ET_0 estimations, further utilization for effective hydrological analysis and irrigation planning.

Trend analysis

Effective organization and management of water resources relies on trend analysis, a crucial instrument in hydrological research. Employing various nonparametric tests, the study sought to evaluate the seasonal and annual variations in ET_0. The study area consists of four seasons: winter (January-February), northeast monsoon (October-December), southwest monsoon (June-September) and summer (March-May) (28). Utilizing R software, version 4. 4. 1, with the trend package, significance was examined at a 5 % level through trend analysis.

Mann-Kendall Test

The Mann-Kendall test is well known nonparametric statistical method for examining the trend of time series data, especially in environmental and hydrological research (29). The test's main advantages are its resistance to effect of inhomogeneous time series and its lack of reliance on data distribution (30). The Mann-Kendall test is intended to detect the presence of a monotonic trend in a time series dataset.

Moreover, the data has no detectable dispersion and the MK test matches missing values (30). Two hypotheses underlie its operation: the time series has a monotonic trend and the data is randomly arranged. The amount of positive and negative differences between data pairs is reflected in the variance of the Mann-Kendall (s) statistic, which is computed in equation 1.

$$S = \sum_{i=1}^{n-1} \sum_{j=k+1}^{n} sign\,(= x_j - x_i)$$

Eqn. (1)

where, 'n' is the 'length of time series', 'X_i' and 'X_2' depicts data points at time 'I' and 'j', respectively and 'sign (X_j-X_i)' is the function that shows +1 if >X_j> X_i,0 if X_j = X_i and -1 if X_j < X_i.

Additionally, S statistic's distribution which is affected by tied values in time series data and variance must be calculated as follows:

$$Var(S) = \frac{n(n+1)(2n+5) - \sum_{i=1}^{m} t_i\,(t_i - 1)(2t_i + 5)}{18}$$

Eqn. (2)

Where, 'n' is the 'quantity of data points', 'm' signifies the 'number of tied groups' and 'ti' represents the' number of tied values within the tied group'. To determine the significance of the observed trend, the test statistic (Z) is calculated using the provided formula.

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}}, & if\ S > 0 \\ 0, & if\ S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}}, & if\ S < 0 \end{cases}$$

Eqn. (3)

Sen's slope estimator

A nonparametric technique, Sen's slope estimator estimates the true slope in time series data (31). It is not necessary that data to follow specific distribution theories. Sen's slope estimator computes median of all possible slopes between value pairs in the datasets to identify slope. Sen's slope estimator utilized for investigating trends in ET_0 magnitude in the study area.

$$\text{Slope } (\beta) = \text{Median } \frac{(X_i - X_j)}{i - j} \quad \text{for all } i > j$$

Eqn. (4)

where, X_i and X_j represents the ET_0 values for years i and j, respectively.

Change point analysis

A statistical technique called Pettit's test is used to identify the moment at which the median of time series data undergoes a substantial shift (32). This non-parametric test is mostly used to find sudden variations in the time series data mean. The annual and seasonal ET_0 datasets were subjected to change point analysis using R software trend package.

The test statistic (Ut, k) is calculated as follows,

$$U_{t,k} = \sum_{i=1}^{k} \sum_{j=k+1}^{n} sign\,(x_j - x_i)$$

Eqn. (5)

where, 't' is the 'length of time series', 'X_j' and 'X_i' stands for the data points at time 'j' and 'i', respectively, k is the year that the change occurs and 'sign (X_j- X_i)' is the function that returns +1 if X >0, 0 if X=0 and -1 if X<0.

The potential change point (KT) where the absolute values of Ut and K are maximum is then found using the Pettitt test.

$$K_T = \max_{1 \le k < n} |U_{t,k}|$$

Eqn. (6)

When P > 0.05, there is a data shift and the significance of the change point is statistically assessed using the estimated p-value or vice-versa.

$$P \approx 2\exp[(-6U^2(K_T))/(n^3 + n^2)] \qquad \text{Eqn. (7)}$$

Principal component analysis

A multivariate statistical method called principal component analysis (PCA) is used to decrease the variables dimensionality while preserving the most of their fluctuation (33). The datasets are broken down into principal components, which are a collection of uncorrelated variables arranged according to variance level. To investigate the meteorological factors affecting the reference evapotranspiration, PCA was carried out using the factoextra and factomine programs in the R software.

To comprehend the dynamics of spatial reference evapotranspiration throughout many seasons, reference evapotranspiration was interpolated and maps were produced (Fig. 2). Significant differences were observed in the basin's annual reference evapotranspiration's geographical distribution. The zonal statistics tool in Arc GIS Pro software was used to determine the average, minimum and maximum reference evapotranspiration for the basin during several seasons.

Results and Discussion

The Amaravathi River Basin's annual and seasonal reference evapotranspiration was analysed for the period 1979 to 2022 using descriptive statistics (Table 1). Analysing regional temperature patterns simply looking at the time series and trends from individual stations is challenging. The findings of the non-parametric test used to evaluate the reference evapotranspiration's temporal patterns are shown in Table 2. Using spatial analysis provides deeper understanding of local and regional trends of climate patterns can be provided.

Trend analysis of ET

The analysis revealed the mean annual ET_0 of 1909.79 mm with a relatively lower coefficient of variation (CV) and higher standard deviation (SD) of 3.14 % and 60.05 indicating relative stability in annual ET_0 trends despite significant seasonal fluctuations (Fig. 3). The pronounced seasonal variability was observed, with the Southwest Monsoon (SWM) period contributing the most to annual ET_0 (36.20 %), followed by the summer season (30.30 %), the Northeast Monsoon (NEM) (18.48 %) and winter (15.02 %). These seasonal contributions underscore the dominant influence of monsoonal rainfall patterns and associated climatic conditions on evapotranspiration dynamics within the basin.

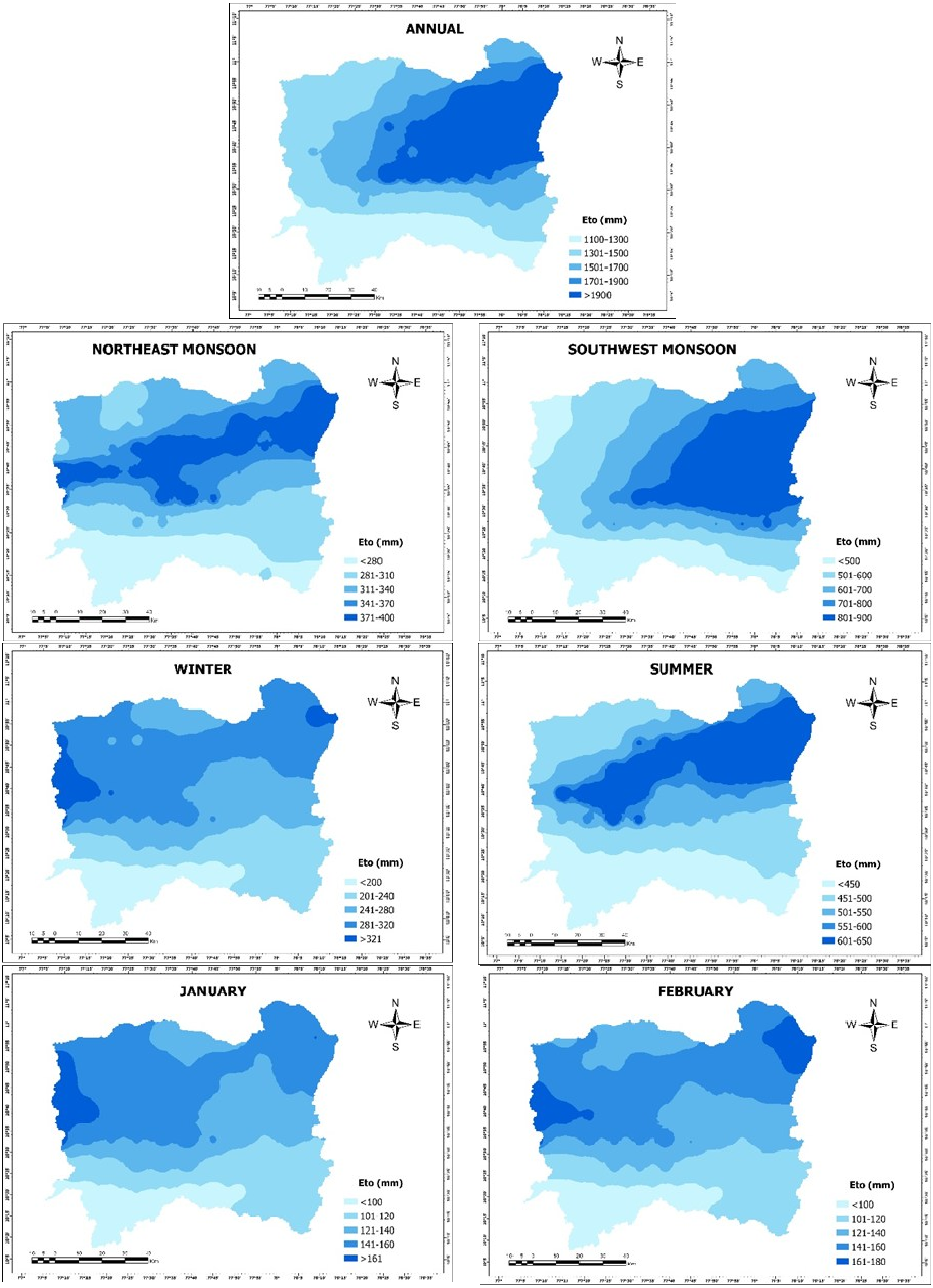
The closer examination of the statistical distribution of ET_0 across seasons revealed varying degrees of asymmetry. While annual ET_0 exhibited near-normal distribution, the winter season displayed pronounced negative skewness, indicating a longer tail towards lower ET_0 values. The summer season, on the other hand, showed moderate deviations from normality. These variations in distributional characteristics reflect the influence of distinct climatic drivers, such as solar radiation, temperature and wind speed, which exhibit varying intensities and patterns across different seasons. Additionally, basin-specific factors, notably cropping patterns, exert a considerable impact on ET flows. This study focuses on a limited region with varied farming systems to analyse these connections. Future study should highlight the measurement of ET in connection to cropping patterns and water production, permitting breakthroughs in irrigation efficiency and sustainable hydrological management. Inter-seasonal variability in ET_0 was found to be higher during SWM (Standard Deviation: 36.11 mm) and summer (SD: 23.33 mm), reflecting the dynamic nature of climatic factors during these periods. The SWM, characterized by intense rainfall and high humidity, experiences significant fluctuations in ET_0 due to the interplay between precipitation, atmospheric moisture and energy availability. Similarly, the summer season, with its high temperature and solar radiation, exhibited substantial variability in ET_0 driven by variations in energy inputs and atmospheric demand.

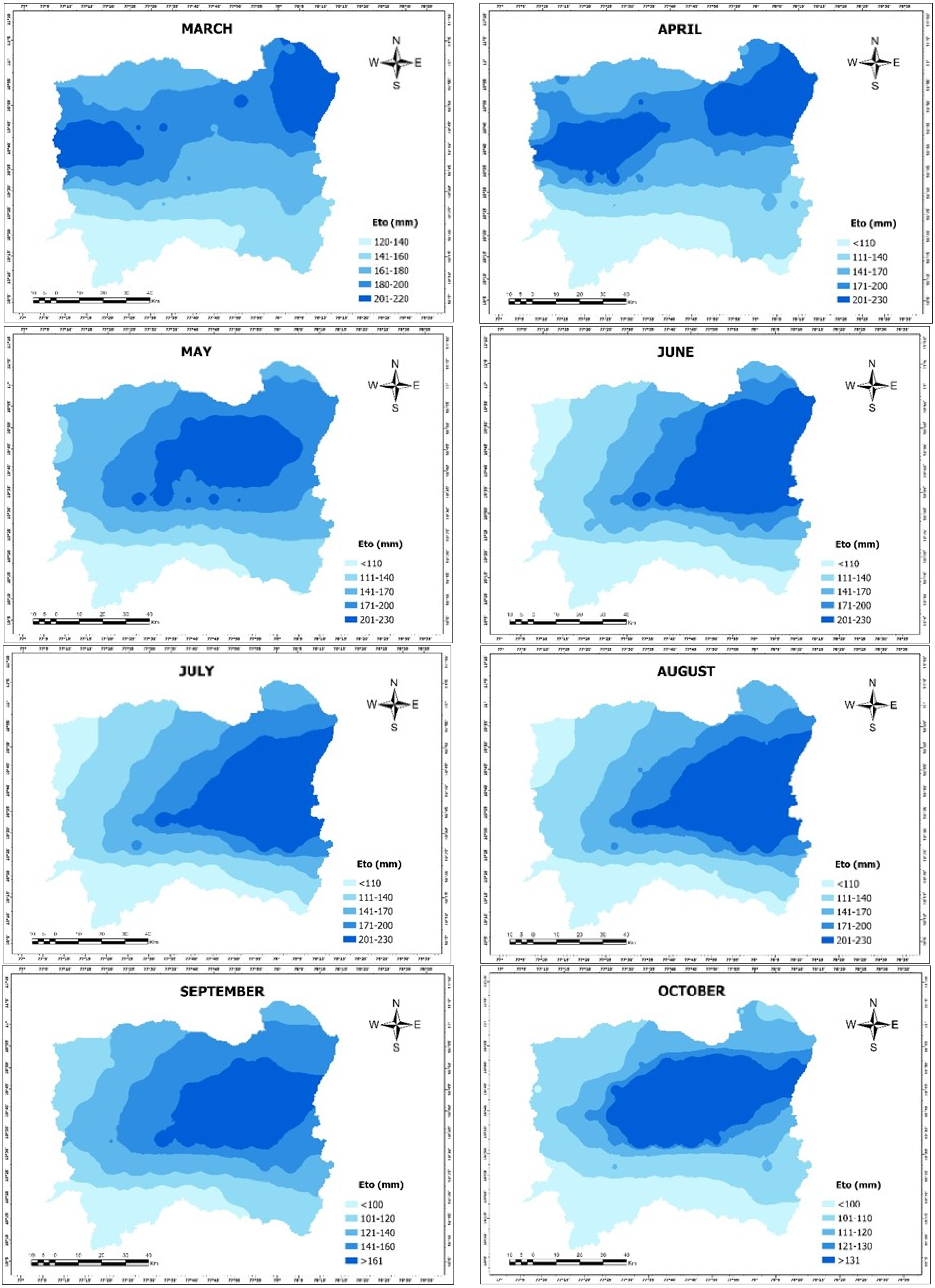
Table 1. Amaravathi River Basin ET_0 descriptive study (1979-2022)

Particulars	Annual	Southwest monsoon	Northeast monsoon	Winter	Summer
Mean	1909.79	691.29	352.99	286.91	578.60
Median	1899.66	693.49	350.28	292.45	584.04
Minimum	1763.29	611.68	302.36	213.16	516.96
Maximum	2030.76	771.29	421.79	321.42	624.41
Kurtosis	0.24	-0.49	-0.20	1.29	-0.12
Skewness	-0.06	0.06	0.42	-1.07	-0.48
Standard deviation	60.05	36.11	26.70	21.54	23.33
Coefficient of variation	3.14	5.22	7.56	7.51	4.03
Contribution	100.00	36.20	18.48	15.02	30.30

Table 2. Trend analysis of the research area's annual and seasonal ET_0

Particulars	Mann-Kendall Test (Z)	Sen Slope (β)	p-value	Trend
Annual	-0.32	-2.35	0.00	Decreasing
Southwest monsoon	-0.22	-1.09	0.03	Decreasing
Northeast monsoon	-0.21	-0.66	0.05	Decreasing
Winter	-0.01	-0.03	0.94	Decreasing
Summer	-0.22	-0.54	0.03	Decreasing


ANNUAL
N
W
E
S
Eto (mm)
1100-1300
1301-1500
1501-1700
1701-1900
>1900
NORTHEAST MONSOON
Eto (mm)
<280
281-310
311-340
341-370
371-400
SOUTHWEST MONSOON
Eto (mm)
<500
501-600
601-700
701-800
801-900
WINTER
Eto (mm)
<200
201-240
241-280
281-320
>321
SUMMER
Eto (mm)
<450
451-500
501-550
551-600
601-650
JANUARY
Eto (mm)
<100
101-120
121-140
141-160
>161
FEBRUARY
Eto (mm)
<100
101-120
121-140
141-160
161-180
Km


MARCH
Eto (mm)
120-140
141-160
161-180
180-200
201-220
APRIL
Eto (mm)
<110
111-140
141-170
171-200
201-230
MAY
Eto (mm)
<110
111-140
141-170
171-200
201-230
JUNE
Eto (mm)
<110
111-140
141-170
171-200
201-230
JULY
Eto (mm)
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111-140
141-170
171-200
201-230
AUGUST
Eto (mm)
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111-140
141-170
171-200
201-230
SEPTEMBER
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121-130
>131

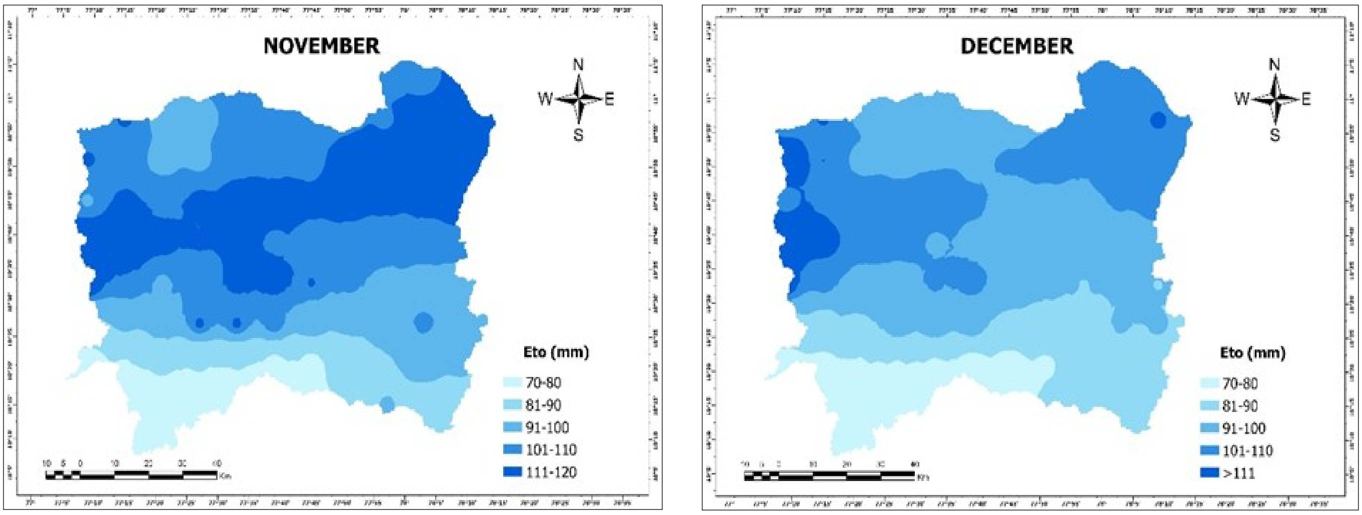

Fig. 2. Spatial distribution of annual, seasonal and monthly ET_o in the Amaravathi river basin.

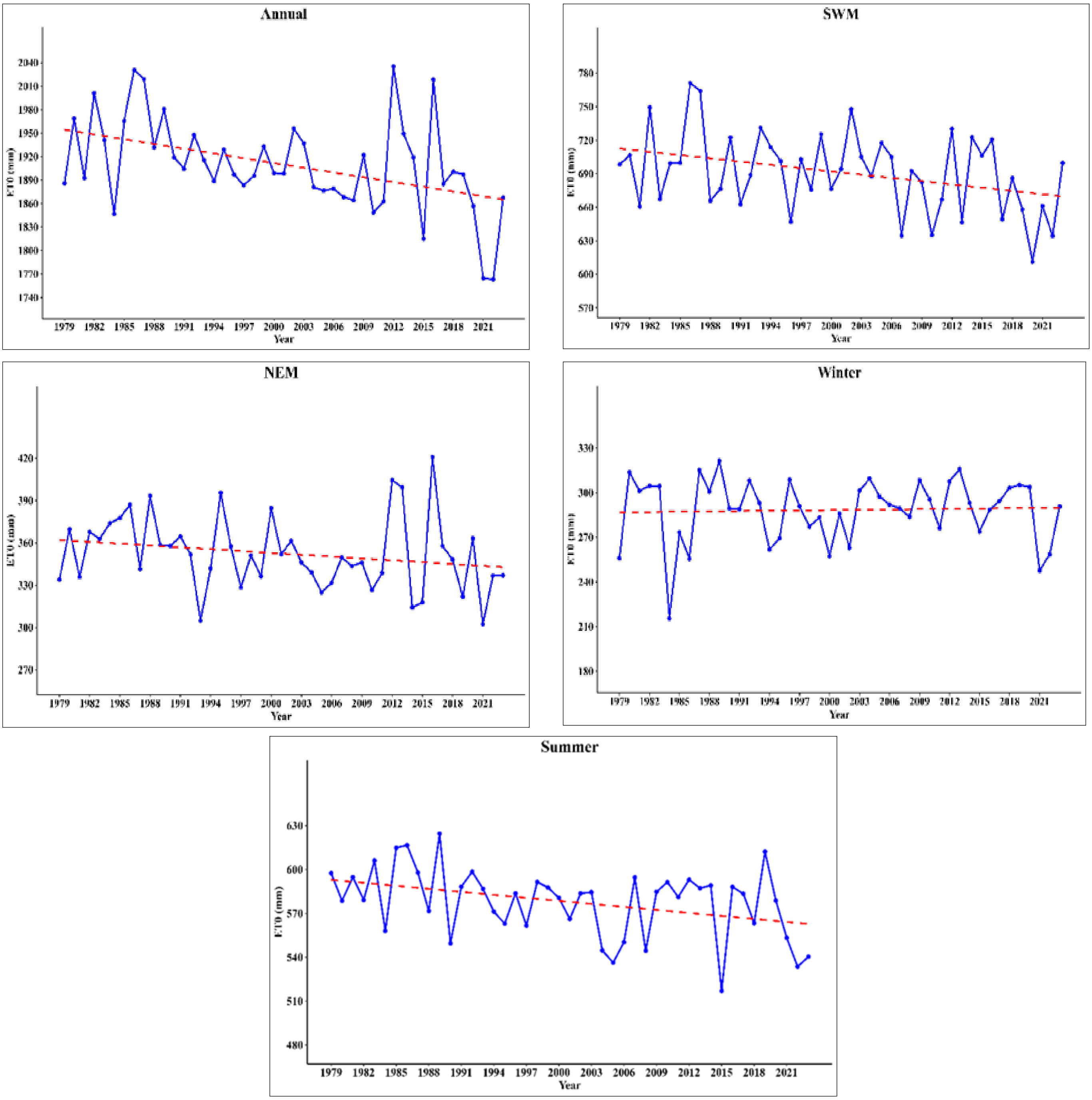

Fig. 3. Trend assessment of ET_0: (a) Annual; (b) Northeastern; (c) Southwest; (d) Winter; (e) Summer.

Mann-Kendall test and Sen's slope estimation

Trend analysis based upon Sen's slope calculation and the Mann -Kendall test showed a statistically significant decline in yearly ET_0 at a rate of 2.35 mm annually ($p < 0.05$), indicating a long-term decline in evapotranspiration potential within the basin. This declining trend was further evident in the seasonal analysis, with significant decreases observed during the SWM (1.09 mm/ year), NEM (0.66 mm/year and summer (0.54 mm/year). However, no significant trend was observed in winter $ET_{0.}$ These findings align with observed climate variability trends in semi-arid regions, where changes in rainfall patterns, temperature regimes and solar radiation have collectively influenced evapotranspiration rates (25).

Pettitt's test identified

Pettitt's test identified significant change point in the ET_0 time series, indicating shifts in the underlying climatic regime. The most prominent change point was observed in 2003 for annual ET_0, suggesting a significant shift in the evapotranspiration regime around the year. Similar change points were identified in the seasonal time series, with the SWM exhibiting a change point in 2006 and the summer season showing a shift in 1993. These change points highlight periods of climatic transitions.

The analysis of the Northeast Monsoon (NEM) reveals significant climatic shifts, with Pettitt's test identifying change points in 1992 and 2002 for the NEM evapotranspiration (ET_0) time series. Although the p-values indicate these shifts are less statistically significant than those in other seasons, they suggest potential climatic changes during this period. In the winter season, a change point was detected in 2002, with trend analysis showing a minimal Sen's slope of -0.034 and an almost neutral Mann-Kendall value of -0.00846. The high p-value (0.943) suggests that trends during this season are statistically insignificant, reflecting a stable evapotranspiration regime. This stability is likely linked to consistent weather parameters, including lower temperatures and solar radiation during winter, which limit changes in ET_0. The summer season exhibits a notable change point in 1993, with a Mann-Kendall value of -0.22199 and a Sen's slope of -0.53754 indicating a decreasing trend (Fig. 4). This trend may result from early onset climate change effects during the 1990s, potentially driven by

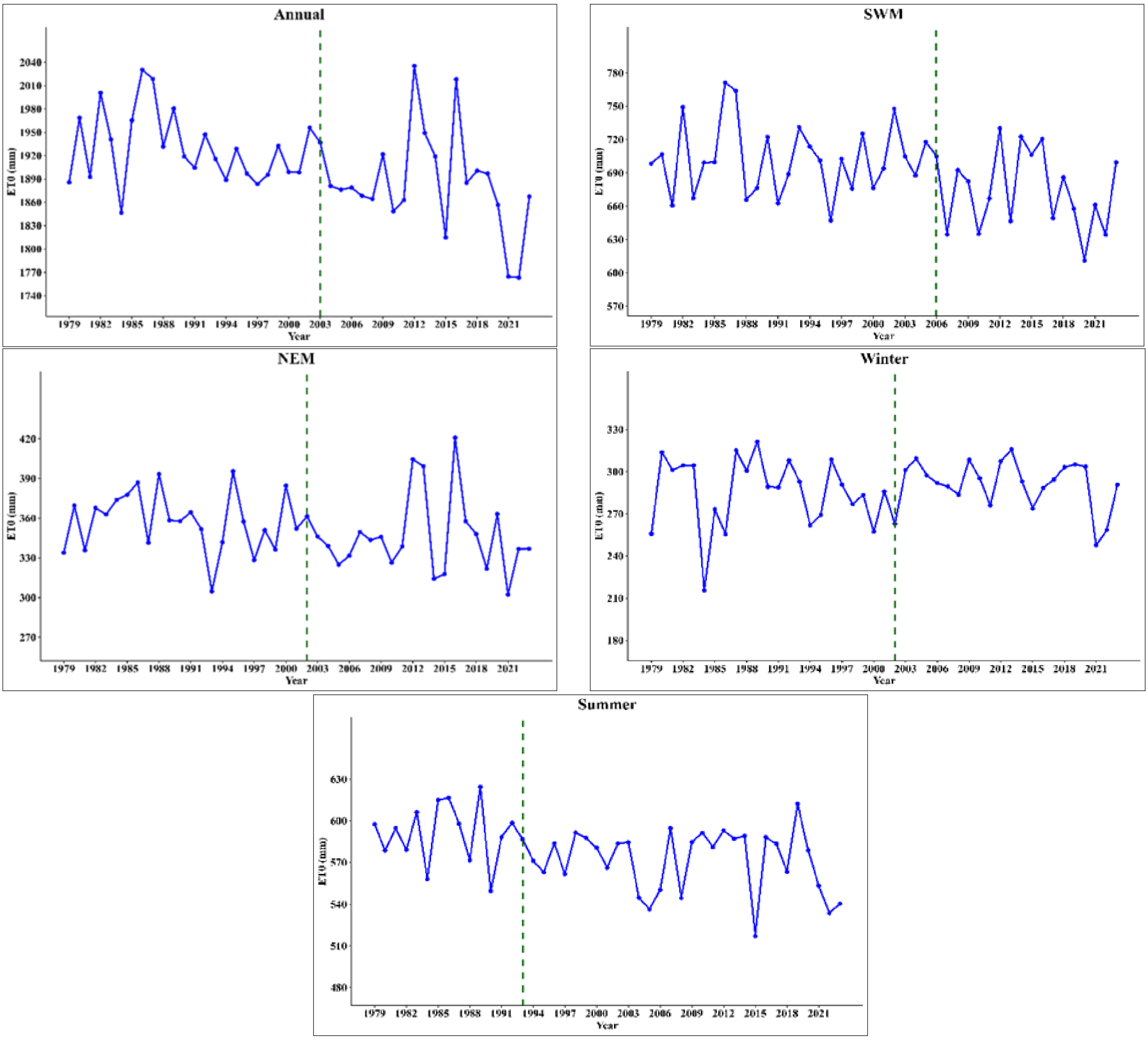

Fig. 4. Identification of the Amaravathi River Basin's ET_0 trend change point (a) Annual (b) Southwest monsoon (c) Northeast monsoon (d) Winter (e) Summer.

increased heat stress or declining precipitation rates. The strong correlations between solar radiation, air temperature and ET_0 underscore their roles in the observed variations during this season.

Relationship between ET_0 and climatic variables

Correlation analysis highlighted a strong positive association between ET_0, solar radiation (SR) and mean temperature (T_{mean}), underscoring the energy-dependent nature of evapotranspiration processes. Elevated solar radiation and temperatures provide the requisite energy for both soil evaporation and plant transpiration, thereby amplifying ET_0 rates. In contrast, rainfall (RF) and relative humidity (RH) exhibited negative correlations with ET_0, indicating their influence in lowering evapotranspiration rates (Fig. 5). Increased rainfall augments surface moisture availability and cools the air through latent heat exchange, thereby diminishing the energy available for evaporation. Similarly, elevated humidity levels reduce the vapor pressure deficit, thus curtailing the evapotranspiration potential. Wind speed (WS), though showing a weaker correlation, still contributes to influencing ET_0 by facilitating moisture transfer from the surface to the atmosphere.

Principal Component Analysis (PCA) further substantiated these observations, with the first principal component (PC1) accounting for 63.24 % of the total variance and strongly linked to ET_0, SR and T_{mean}. This component effectively encapsulates the energy-driven mechanisms underpinning ET_0, reaffirming the critical role of temperature and radiation in its dynamics. The second principal component (PC2), which explains 18.38 % of the variance, was associated with WS and RF, reflecting the significance of aerodynamic and precipitation-related factors in modulating ET_0 (Fig. 6). The cumulative variance explained by these two components (81.63 %) underscores PCA efficacy in encapsulating the key climatic drivers influencing evapotranspiration variability within the basin.

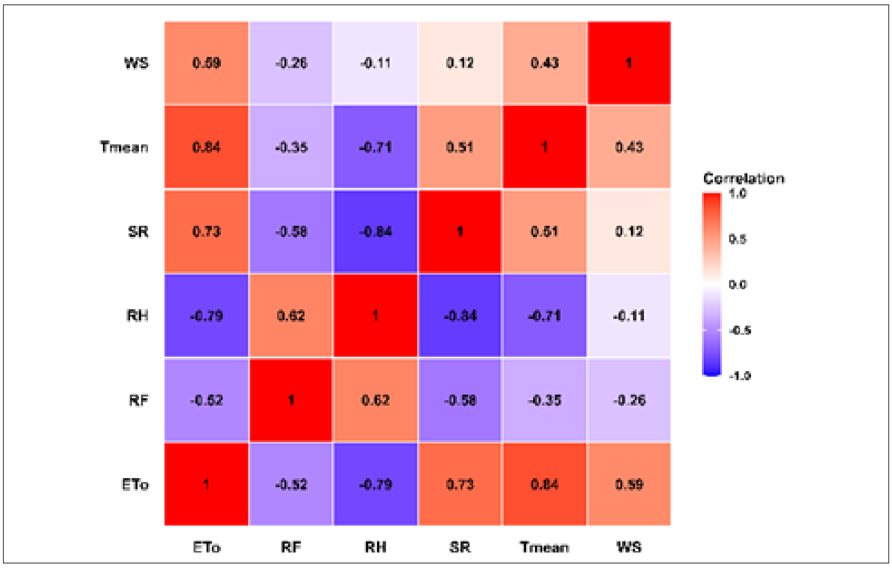

Fig. 5. Correlation analysis between weather variables and ET_0.

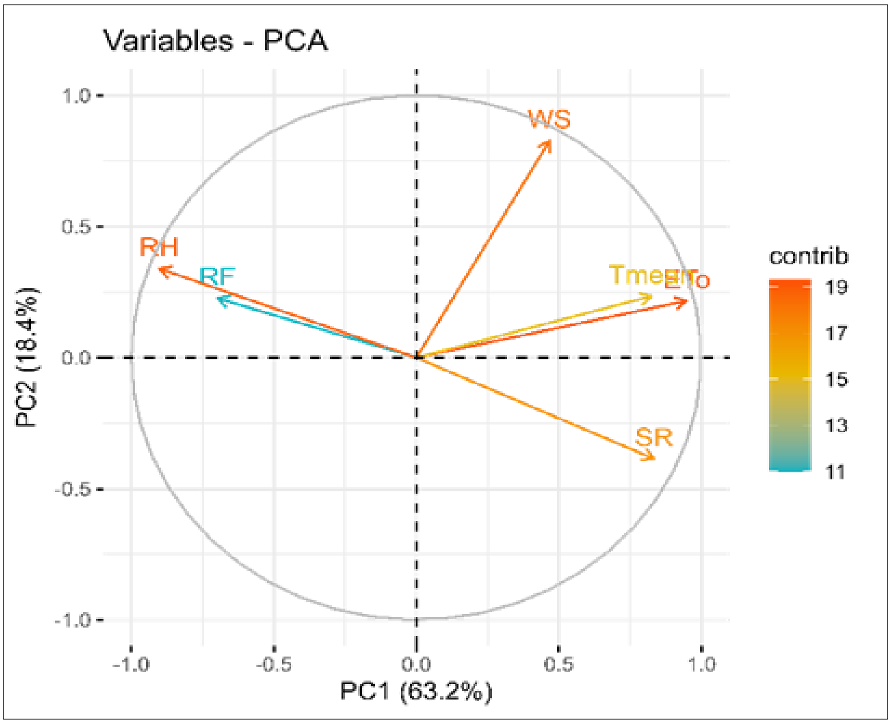

Fig. 6. PCA analysis of weather variables in the study area.

Conclusion

This 44-year assessment (1979-2022) of reference evapotranspiration (ET_0) trends in the Amaravathi River Basin reveals a significant decline of 2.35 mm/year, with the most pronounced reductions occurring during the Southwest Monsoon (SWM), Northeast Monsoon (NEM) and summer seasons. This downward trend corresponds to reduced solar radiation and shifting thermal dynamics, characteristic of semi-arid environments. Seasonal analysis identifies SWM as the most variable, influenced by complex interactions among precipitation, humidity and energy fluxes. While solar radiation and temperature are primary drivers of ET_0, precipitation and humidity play a crucial role in moderating atmospheric moisture demand. These findings emphasize the critical need for ET-based irrigation strategies to enhance water efficiency and strengthen resilience against hydrological fluctuations.

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Authors' contributions

GS wrote entire manuscript text of review, utilization of software for preparing figures; KV gave conceptualization of the idea and edited the manuscript; SS[1] and MJ reviewed the paper and shared their inputs for further upscaling, RJ and PP provide the guidance for using the software, SS[2] guided for doing analysis and reviewed the manuscript. [SS[1] -S Selvakumar & SS[2]- S Shakthivelan]

Compliance with ethical standards

Conflict of interest: Authors declare there is no conflict of interest

Ethical issues: None

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