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RESEARCH

Spatial distribution of the trends in potential evapotranspiration and its influencing climatic factors in Iraq

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Abstract
Understanding the spatial variations in potential evapotranspiration (PET) and its influencing climatic variables is essential for sustainable agriculture and water resources management. However, little published research has investigated the alternation of PET due to climate change in the case of Iraq. The objective of the present study was to analyze the spatial trends in annual and seasonal PET in Iraq. Accordingly, the latest global ERA5-Land dataset of the European Centre for Medium-Range Weather Forecasts for 1981–2021 was employed. The PET was estimated using the FAO-Penman–Monteith method. The modified Mann–Kendall statistical test was applied to evaluate the significance of the trends in PET, which can separate unidirectional trends caused by climate change from the natural variability of climate. The attained results indicate that: (1) Over the past four decades, the annual and seasonal PET witnessed a significant increasing trend in almost all of Iraq, except for the alluvial plain in the eastern and southeastern parts. (2) The increasing trend in PET confirmed the patterns of the trend significance, with the highest increase of 0.28–0.65 mm/decade in southwest Iraq. (3) Summer had the highest upward trend of 0.35–0.65 mm/decade, followed by spring, autumn, and winter. (4) The air temperature was the predominant driving factor of rising PET, showing a positive correlation ranging from 0.77 to 0.88 and a contribution of 26 to 94%, mainly in the south, central, and northwest regions. The reverse contribution of wind speed and surface pressure to PET, particularly in the southeast and southwest, remains offset by the influence of air temperature and net solar radiation. Overall, the PET has risen drastically due to global climate change, indicating the potential for increased atmospheric water demand in the region.

1 Introduction

Potential evapotranspiration (PET) is a crucial process of the global water cycle and one of the most direct indicators of climate change. Over the past century, increased greenhouse gas concentrations in the atmosphere due to anthropogenic activities have led to global warming. Accordingly, the global mean surface air temperature has risen by about 0.85 °C from 1880 to 2012 (Stocker 2014; Hennessy et al. 2022). The alternations in PET also occurred due to its direct linkage with various atmospheric factors (Pascolini-Campbell et al. 2021; Wang et al. 2021). Considering the importance of PET, the influence of climate change on the changeability in PET has received increasing attention from numerous scholars and governments worldwide. It had reported that the variable characteristics of PET are closely related to the variations in climatic factors, such as solar radiation (SR), air temperature (AT), wind speed (WS), and relative humidity (RH) (Hosseinzadeh Talaee et al. 2014; Ahmad et al. 2017; Valipour et al. 2020; Tang and Tang 2021; Jerin et al. 2021; Anwar et al. 2021). However, the direction and magnitude of alternation in PET might vary significantly over different regions, which hence can cause negative implications for agricultural production and water availability (Li et al. 2021; Pour et al. 2020). Therefore, analyzing the spatial and temporal variations in PET is necessary for understanding the effects of climate change on the regional characteristics of the hydrological cycle, especially in the vulnerable regions to global climate change.

PET represents a measure corresponding to water vapor removal from land, vegetation, and water bodies to the

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atmosphere by the evaporation and transpiration processes (Zhang and Wang 2021). In addition, it can be described theoretically as the flux of water vapor under ideal conditions, e.g., uniform plant height and coverage when the water supply to the soil surface is unlimited (Allen et al. 1998). Therefore, PET is commonly used to understand the interaction between water and earth energy processes (Jiang et al. 2019). Besides, PET is influenced primarily by climatic, botanical, and hydrological factors. A clear example of the important climatic factors is SR, WS, and AT, whereas important biological factors include crop density and vegetation type. PET also plays a vital role in terrestrial water fluxes and water storage, for instance, soil moisture, surface runoff, and groundwater (Singer et al. 2021). Runoff and groundwater recharge might be affected by the changes in PET (Salman et al. 2017) and hence might affect crop water availability and crop growth. Accordingly, PET is imperative for determining irrigation scheduling and crop water requirements and estimating the water budget (Allen et al. 1998; Zhang and Wang 2021). PET is also essential for computing the actual evapotranspiration, representing the amount of water quantity removed from a surface, which is necessary for evaluating agricultural water demand (Khaydar et al. 2021; Ferreira et al. 2021). It is also required to estimate the aridity index and help understand the regional drought and dry conditions (Um et al. 2020). PET is an input for various applications and models in hydrology, agronomy, ecology, and agrometeorology (Herman et al. 2018; Wambura et al. 2018). Thus, knowledge of the spatial changes in PET and its controlling climatic variables is essential for water resources management, sustainable agriculture, and climate-related hazards assessment.

Iraq, situated in Western Asia, is notably experiencing water shortages. Since the early 1970s, the country has suffered from a gradual decrease in the annual streamflow of its two primary water resources, the Tigris and Euphrates rivers, caused mainly by human-intervention activities in upland catchments (i.e., dam constructions) and climate change (Al-Ansari et al. 2018; Al-Hasani 2021). Consequently, water security has become the biggest challenge facing the development of Iraqi agriculture and the economy (Salman et al. 2021). Iraq is considered highly vulnerable to global climate change, which has a predominantly arid and semi-arid climate, particularly in the central and southern regions, where temperature extremes and precipitation variability occur frequently (Salman et al. 2017, 2018). The increasing intensity of extreme weather events, namely heat waves, dust storms, persistent droughts, and flash floods, have been reported throughout the past 20–30 years in Iraq (Tolba and Najib 2009; Salman et al. 2018). Consequently, water availability and agricultural productivity are affected severely, putting thousands of small producers and smallholder farmers at the risk of hunger, poverty, and instability, especially in vulnerable communities in rural areas of Iraq. Hence, studying the spatial changes in PET and the influencing climatic factors can provide better insight into the possible adaptation actions to unavoidable effects of climate change on the hydrological cycle and help for effective water resources planning and sustainable agricultural systems in Iraq.

The reviewed literature showed only a few published studies in Iraq on PET trends assessment at annual and seasonal scales. Saud et al. (2014) investigated the spatial and temporal trends in PET for Al-Anbar Province, located in the west of Iraq, from 1980 to 2010 based on several methods for estimating PET and found that the Ivanov method obtained the best results for calculating PET. Al-Sudani (2019) computed the mean monthly PET based on different time duration ranging between 15 and 73 years for Iraq using the Thornthwaite method based on only monthly average AT and reported that PET had a positive relationship with surface temperature. Hamadamin et al. (2021) assessed the changes in annual and monthly PET using the FAO-PM method at spatial and temporal time scales in the northern region of Iraq (i.e., Dohuk, Erbil, and Sulaymaniyah provinces of the Kurdistan Region of Iraq). Results revealed significant positive and negative trends in the annual PET for only about 20% of studied stations and found that the main contributor to trends was WS.

Nevertheless, most previous studies had the shortcoming of the limited study region, short duration, and specific methodology. The trend directions in the mentioned studies were mainly analyzed using trend tests such as linear regression, Spearman's rho, and classical Mann–Kendall. However, the significance of trends assessed based on the MK test is affected by the autocorrelation in hydro-meteorological series (Kumar et al. 2009). It is primarily due to the natural variability of climate, which can cause an overestimation of trend significance in auto-correlated climate data series. It is a significant drawback of using the MK test in most previous studies. Thus, the modified version of the classical Mann–Kendall (MMK) test, such as the MMK test proposed by Hamed (2008), should be applied to consider the influence of a significant autocorrelation coefficient present in the studied time series using the MK test (Salman et al. 2017; Nashwan et al. 2019). Yet, another considerable limitation is that most empirical methods for estimating PET in these studies depend on AT or SR. There is a notable lack of analyzing the statistical trends of PET for the whole of Iraq based on the recommended combination-based method by the Food and Agricultural Organization of the United Nations (FAO) Penman–Monteith (P-M) method. The estimation of PET can be complex since PET represents a measure of an integrated influence of several meteorological variables. In addition, due to the lack of observed data for the study area, the effect of other influencing agrometeorological parameters, particularly vapor pressure, WS, and RH, was not considered in previous studies. Several empirical mass-transfer-based, temperature-based, and radiation-based methods had used for calculating PET worldwide. However, the combined FAO P-M method is the standard and the most widely accepted procedure for computing PET, particularly in arid and semi-arid regions (Wang et al. 2017). The FAO P-M method has been used in the present study considering the various influencing climatic variables on PET to overcome this considerable drawback. The spatial distribution of trends in PET and its controlling factors under a changing climate remains ambiguous and still not explored in the considered region of Iraq. Despite this significant gap, no previous published study has analyzed the spatial changes in PET and its controlling driving climate factors, using the standard FAO P-M method and considering the influence of serial autocorrelation in PET time series over entire Iraq.

Based on the above discussion, the objectives of this study are (1) to estimate the annual, seasonal, and monthly PET in Iraq for the period 1981–2021 based on the FAO P-M method; (2) to analyze the spatial trends in the estimated PET from 1981 to 2021 at annual and seasonal scales over different regions of Iraq using the MMK trend test to eliminate the effects of the natural variability of climate; and (3) to identify the controlling climate paraments responsible for spatial trends in PET in Iraq using the Pearson correlation and linear regression methods. The findings can provide a comprehensive understanding of climate change effects on PET and helpful information for adaptation planning, sustainable agriculture, and water resources management in Iraq.

2 Data description and methods

2.1 Study area

Iraq, situated in the Middle East and West Asia, is bordered by Turkey to the north, Iran to the east, Syria and Jordan to the west, and Kuwait and Saudi Arabia to the South, as shown in Fig. 1. Iraq, also commonly known as the land between two rivers, Mesopotamian, contains the Tigris and Euphrates Rivers and their tributaries, which are the most crucial water resources in the country. The inflow of these two rivers jointly created the Mesopotamian alluvial plain of Iraq, supplying environmental water to the unique ecosystem of the Iraqi wetlands or Mesopotamian Marshlands in the southern region. The country covers an area of 434,128 km^2, which varies in elevation from − 74 m in the south to 3583 m in the northern and northeastern mountainous ranges (see Fig. 1). Iraq is classified primarily as an arid and semi-arid country. According to the Koppen climate classification, Iraq has various climatic zones, including warm arid, hot semi-arid, and the warm Mediterranean (Salman et al. 2019). However, its main characteristic climate zones are the semi-arid climate, desert climate, and Mediterranean climate. Summer is generally extended from (mid-May to early September) regardless in the northeast mountainous areas where it is shorter than in other parts, starting from (June to August); winter is a short season, lasting from (December to February). Spring from (March to early May) and autumn from (mid-September to November) are transitional and short seasons. July and August are the hottest months in Iraq, while December and January are the coldest (Salman et al. 2018). The temperature varies spatially and seasonally from 18 °C in winter to more than 44 °C during summer. The precipitation is seasonal and occurs between November to April. The mean annual rainfall over Iraq fluctuates from less than 150 mm for most of the country, especially in the arid southwest, to more than 400 mm in the humid Northeast. Therefore, Iraq has relatively high evaporation and evapotranspiration rates.

2.2 Data sources

The present study used the reanalysis of gridded data. For this purpose, the most recent European Reanalysis version 5 (ERA5) (Muñoz-Sabater et al. 2021) dataset was employed. The ERA5 is the fifth edition of European Reanalysis data, developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). It is a global dataset of many land and atmospheric parameters for the past four decades at a specific resolution (spatial grid of 0.1°; 9 km). The dataset of ERA5 consists of satellite historical observation data with advanced numerical prediction models and other available observatory gauging records. ERA5 data can provide insight into different climate conditions and accurate representations of the climate and weather at standard intervals through uniform grids with a reasonable resolution both temporally and spatially over an extended period. The study used several climatic variables of the ERA5-Land dataset to estimate the PET using the FAO P-M method, including AT, WS, dew point temperature (DT), atmospheric surface pressure (ATP), and surface net and thermal SR. One of the advantages of using ERA5 data is that it allows obtaining climatic variables in un-gauged locations in Iraq, especially in the remote desert and mountainous areas. The Iraqi Meteorological Organization and Seismology organization has more than 50 gauging stations distributed over Iraq. However, they have a notable missing observed data, particularly for years of subsequent wars. Another advantage of applying ERA5-Land is the availability of its dataset. Accordingly, this study adopted the reanalysis ERA5-Land of gridded monthly average data.

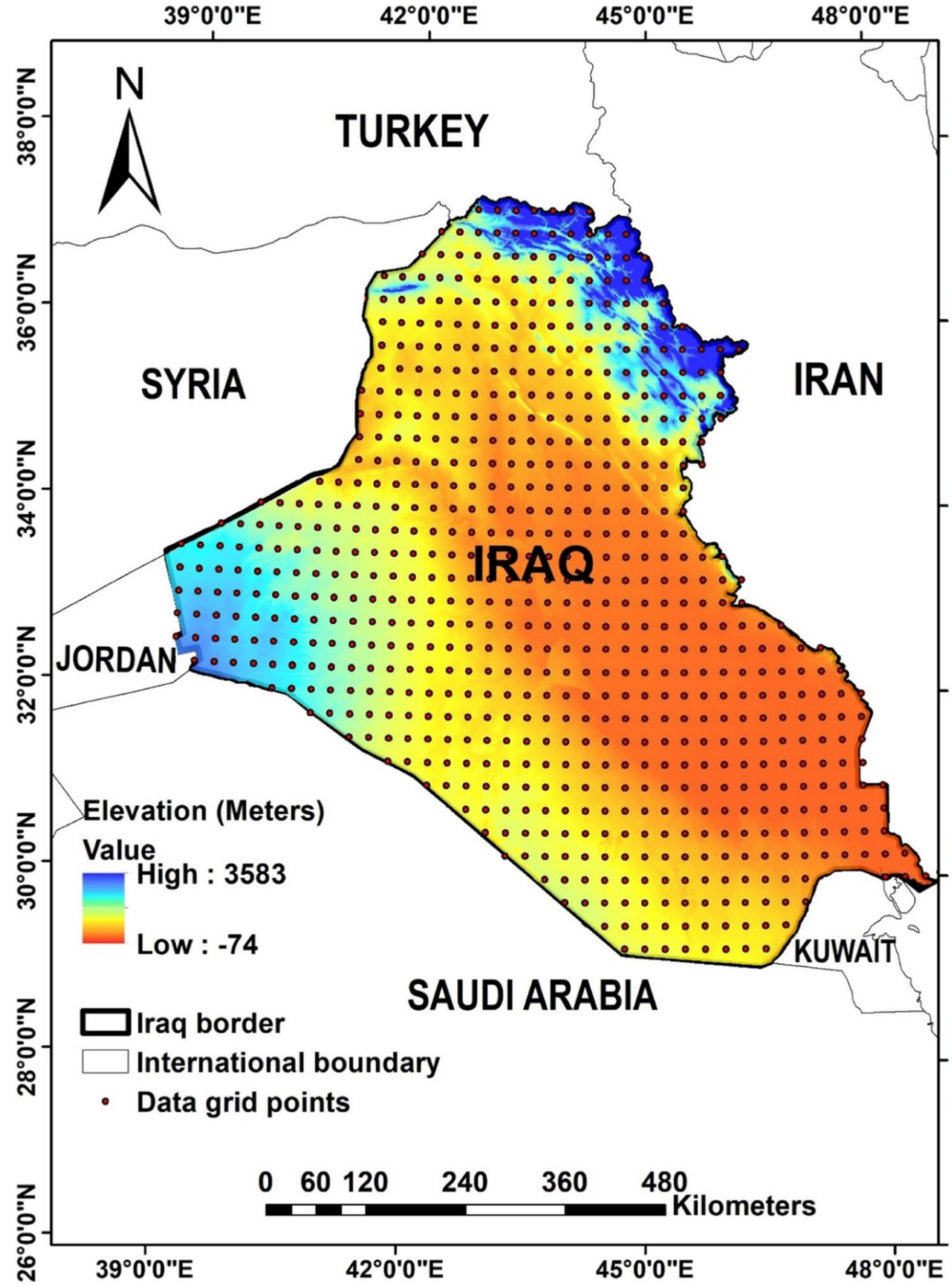


Fig. 1 The location of Iraq and the spatial distribution of its topography. Red dots represent the ERA5 grids for which PET data was estimated

2.3 Methods for estimating potential evapotranspiration

2.3.1 FAO Penman–Monteith method

The FAO Penman–Monteith (FAO P-M) formula is adopted to estimate the daily PET in this study. The Food and Agricultural Organization (FAO) of the United Nations developed and recommended the FAO Penman–Monteith equation (Allen et al. 1998). It is considered the standard method for calculating PET (Muhammad et al. 2019). Therefore, it has been used widely in numerous regions due to its consistency, accuracy, and robustness compared to that empirical radiation-based and temperature-based methods. The FAO P-M equation requires seven meteorological parameter data to calculate daily PET values, i.e., AT, DT, WS, ATP, and surface total SR. PET rate is estimated using the FAO P-M method from a hypothetical reference grass with an assumed height of 0.12 m, an albedo of 0.23, and a fixed surface resistance of 70 (s/m). The FAO-PM stander method can be expressed in Eq. (1):

$$PET_{x,t} = \frac{0.408\Delta\left(R_n - G\right) + \gamma\left(\frac{37}{T_a+273}\right)u_2(e_s - e_a)}{1\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where PET is in mm/day, R_n is net SR (MJ m^{-2}/day), G is the soil heat flux density (MJ m^{-2}/day), γ is the psychrometric constant (kPa/°C^{-1}), T_a is AT measured at 2 m (°C) in K, Δ is the slope of the saturation vapor pressure–temperature curve (kPa/°C^{-1}), e_s is saturation vapor pressure (kPa), u_2 is the average daily WS (m s^{-1}) at 2-m height above the ground surface, and e_a is actual vapor pressure (kPa). The measured daily WS has been converted from (10 m) height above the ground surface computed at 2-m value, as shown in Eq. (2):

$$u_2 = u_z\left(\frac{4.87}{\ln(67.8_z - 5.42)}\right) \quad (2)$$

where u_z represents the measured WS at z m height above the ground surface (m/s) calculated as $u_z = \sqrt{u^2 + v^2}$. The given WS data is measured at z equals 10 m. Also, e_a and e_s are calculated as a function of dew point and air temperature (T_{dew}) in °C (converted from the provided data in K), as can be given in Eqs. (3) and (4):

$$e_s = 0.6108\exp\left[\frac{17.27 - T_a}{T_a - 237.3}\right] \quad (3)$$

$$e_a = 0.6108\exp\left[\frac{17.27 - T_{dew}}{T_{dew} - 237.3}\right] \quad (4)$$

(Δ), the slope of the saturation vapor pressure curve (KPa °C^{-1}), is estimated, as Eq. (5):

$$\Delta = \frac{4098e_s}{(T_a + 237.3)^2} \quad (5)$$

Also, (γ), the psychrometric constant (KPa/°C^{-1}), is calculated as Eq. (6):

$$\gamma = \frac{C_p \times P}{\varepsilon \times \lambda} \quad (6)$$

where C_p is the specific heat of air at constant pressure or a value of 1.013 × 10 − 3 MJ kg^{-1} per °C, P is atmospheric pressure (kPa), ε is equal to 0.622, or (molecular weight of water vapor/dry air), and λ is the (latent) heat of evaporation or vaporization that is equal to a value of 2.45 MJ kg^{-1}. In addition, the net radiation is in MJ m^{-2}, and R_n is calculated by the difference between net thermal radiation and net solar radiation, as given in Eq. (7):

$$R_n = R_s - R_t \quad (7)$$

where R_t is calculated as: $R_n = R_s + R_t$. Soil heat flux, G, is calculated for (daytime and nighttime) as shown in Eq. (8):

$$G = \left\{ \begin{array}{l} G_{\text{day}} = 0.1 \times R_n \\ G_{\text{night}} = 0.5 \times R_n \end{array} \right\} \quad (8)$$

where the soil heat flux represents 50% throughout the night, as the nighttime heat flux is negative (increase), and 10% is the surface net SR throughout the day. The SR is also utilized to describe nighttime and daytime times (Singer et al. 2021).

2.4 Trend analysis methods

2.4.1 MMK trend test

The MK test is a nonparametric trend test used to detect a trend in the PET time series data. The MK test is employed to statistically investigate if there is a significant downward or upward trend of the variable time series over time. Originally, Mann (1945) devised this nonparametric statistical test, and later it was developed by Kendall (1975). The importance of the MK test is related to its robustness over several statistical parametric tests and insensitivity to missing data in time series. Thus, it has been widely used in the literature to detect trends in PET time series. Only the relative values of all terms in the series, that is, $X = (X_1, X_2, X_3 \ldots X_n)$, are considered by the test to be analyzed (Al-Hasani 2021). The MK test statistic S is expressed as described below:

$$S = \sum_{k=1}^{n-1} \sum\nolimits_{i=k+1}^{n} sign\left(X_i - X_k\right) \quad (9)$$

where n represents the dataset's number; X_i and X_k denote values of data in series at the time, i and k, respectively. If $n \geq 8$, the statistic S is independent and almost generally distributed with the mean and variance, and sign $(X_i - X_k)$ can be computed as follows:

$$\text{sign}(X_i - X_k) = \begin{cases} +1 if (X_i - X_k) > 0 \\ 0 if (X_i - X_k) = 0 \\ -1 if (X_i - X_k) < 0 \end{cases} \quad (10)$$

The variance of S donated by σ^2 as shown in formula (11):

$$\sigma^2 = \frac{n(n-1)(2n+5)}{18} \quad (11)$$

Hence, the standardized Z-statistic is expressed as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases} \quad (12)$$

where Var (S) represents the variance of S, and the Z value is used to evaluate the significance of the trend. For standard, the absolute value of Z more than 1.96 (2.58) denotes the significance of the trend at 1% (5%) significance levels. Also, the sign of Z indicates the trend direction. A negative (positive) value of Z indicates a downward (upward) trend (Radziejewski and Kundzewicz 2004).

The MMK test first eliminates the identified trend in the considered PET time series detected by MK (Hamed 2008). Then, the detrended PET time series is expressed as follows:

$$Z_i = \phi^{-1}\left(\frac{R_i}{n+1}\right) \tag{13}$$

where R_i is the equivalent normal variants of rank, and $\phi^{-1} is$ the inverse standard normal probability distribution function of data. The Hurst coefficient (H) of the series is calculated as follows:

$$\rho_l = \frac{1}{2}\left(|l+1|^{2H} - 2|l|^{2H} + |l+1|^{2H}\right) \tag{14}$$

where ρ_l indicates the autocorrelation function of lag l for a provided H which is estimated through Eq. (13). Subsequently, the mean and standard deviation of H (0.5 value) is used to discover the significance of H (Koutsoyiannis 2003). When, H is statistically significant, the biased estimate of variance ($V(S)^H$) is computed as follows:

$$V(S)^{H'} = \sum_{i<j} \times \sum_{k<1} \frac{2}{\pi} \sin^{-1}\left(\frac{\rho_l = |j-i| - \rho|i-l| - \rho|j-k| + \rho|i-k|}{\sqrt{(2-2\rho|i-j|)(2-2\rho|k-l|)}}\right) \tag{15}$$

To get the unbiased estimate of variance based on using a bias correlation factor (B), as follows:

$$V(S)^H = V(S)^{H'} \times B \tag{16}$$

Eventually, the MMK test trend significance is estimated by replacing $V(S)^H$ instead of Var (S) in Eq. (12).

2.4.2 Sen's slope estimator

Sen's slope estimator is a nonparametric test used to assess the trend magnitude in the time series data. The trend magnitude in a chosen time series is estimated using a median-based slope model proposed by Sen (1968) and additionally developed by Van Belle and Hughes (1984). The true slope of an existing trend (e.g., the amount of change per year) in the PET series can be calculated as in Eq. (17):

$$Q_i = \text{Median}\left[\frac{x_j - x_k}{j-k}\right] f\ or\ k = 1\ to\ N \tag{17}$$

where x_j and x_k represent data values at times j and k ($j > k$), respectively. Also, the variation in a PET time series is calculated as the median slope (Q_{median}) of N slopes estimated from all likely grouping of pairs for the examined dataset, as follows:

$$Q_{\text{median}} = \left\{ Q|(N+1)/2|\ if,\ N\ is\ \text{odd} \frac{Q|N/2| + Q|(N+2)/2|}{2}\ if,\ N\ is\ \text{even} \right\} \tag{18}$$

A negative (positive) value of Q_i denotes a decreasing (increasing) trend in the time series.

2.4.3 Pearson's correlation

The Pearson correlation coefficient is a statistical test widely used to measure the statistical relationship between two numerical variables. The Pearson correlation assigns a value from − 1 to + 1, with the value of 0 representing no correlation between the two variables. It is important to mention that a zero value does not indicate any relationship, but it suggests that there is no relationship. − 1 denotes total negative correlation, and + 1 denotes total positive correlation (Schober et al. 2018).

Pearson correlation between two parameters X and Y is given by Eq. (19):

$$\text{Correlation}(X, Y) = \frac{Sxy}{\delta x \times \delta y} \tag{19}$$

where s_{xy} is the covariance between X and Y, and $\delta x \times \delta y$ is standard deviation of X and Y, which is computed as follows:

The Pearson correlation coefficient can be given, as follows:

$$r = \frac{n \times \sum_{i=1}^{n} x_i y_i (\sum_{i=1}^{n} x_i) \times (\sum_{i=1}^{n} y_i)}{\sqrt{n \times \sum_{i=1}^{n} x^2 - (\sum_{i=1}^{n} x_i)^2} \times \sqrt{n \times \sum_{i=1}^{n} y^2 - (\sum_{i=1}^{n} y_i)^2}} \tag{20}$$

2.4.4 Spatial interpolation

The inverse distance weighting (IDW) interpolation method of ArcGIS 10.6 was used to present the spatial variability of PET and other related meteorological factors in the current study. Unlike other interpolation methods, such as ordinary kriging and spline, the IDW method provides less mean error (Chen and Liu 2012).

3 Results

The trend analysis of spatial changes in annual and seasonal PET has illustrated in the following sections. The average daily PET was first estimated at each grid point using the FAO P-M method at annual, seasonal, and monthly time scales. The significance of the trend of PET at each grid cell was analyzed using the MMK trend test at 95% and 99% confidence levels. Figures also presented the spatial distribution patterns of trends and the significance of the detected trends in the subsequent sections. Additionally, results related to the spatial distribution of the rate of the changes attained based on Sen's slope method were observed to be significant by the MMK test. The contribution rate and correlation between PET and the selected meteorological parameters influence the PET using Pearson's correlation coefficient and linear regression methods presented in the following sections.

3.1 Spatial patterns of annual, seasonal, and monthly potential evapotranspiration

The PET was estimated using the FAO P-M method for all grid points in Iraq regions. The spatial patterns of annual and seasonal average daily PET from 1981 to 2021 for the whole country are presented in Figs. 2 and 3. The inverse distance interpolation (IDW) method using ArcMap 10.6 was applied to prepare the maps. The interpolated annual mean PET values have been divided into seven classes varying from 0.76 mm/day in the northeastern mountainous region to 21 mm/day in the southern desert region.

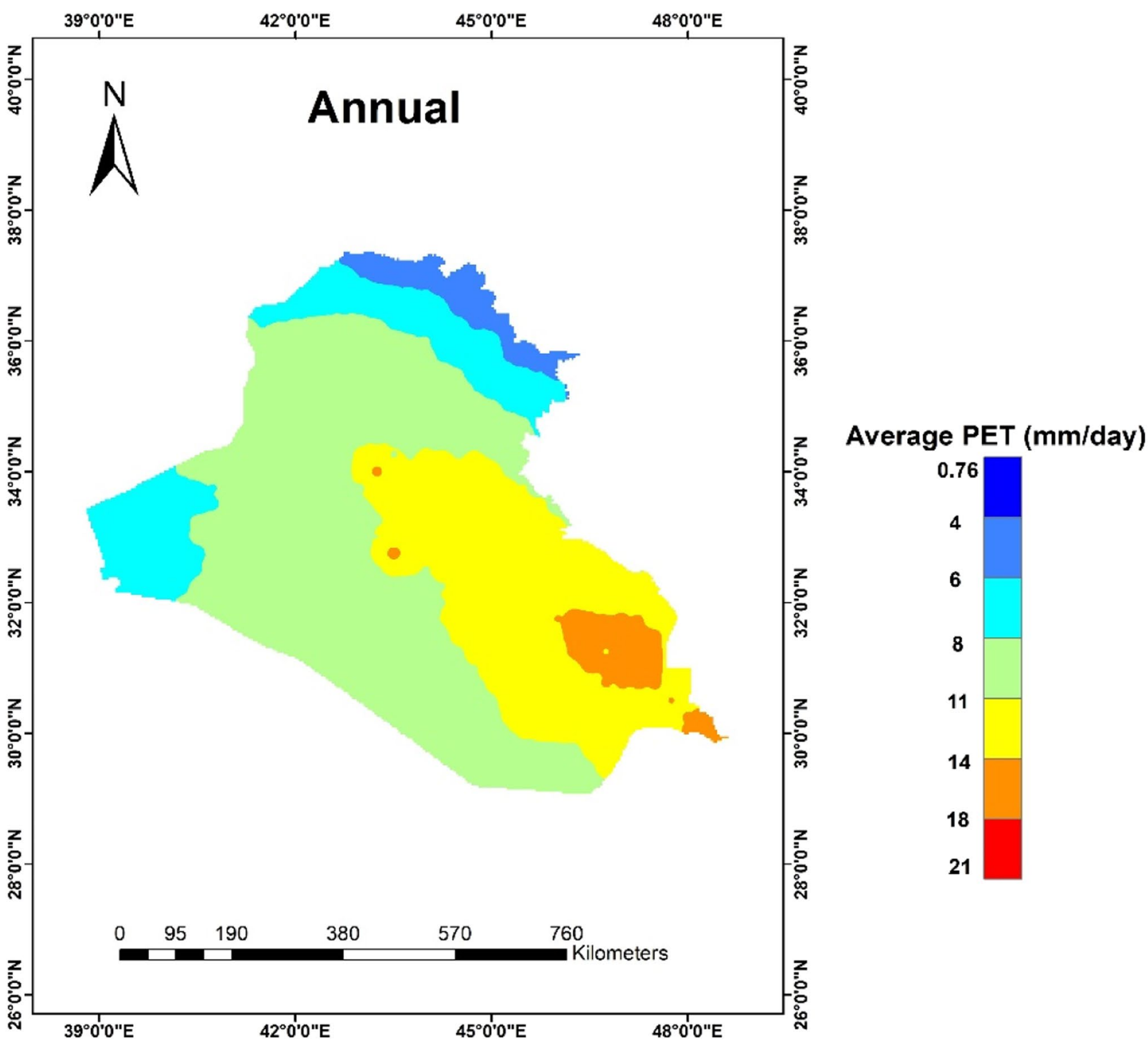


Fig. 2 Spatial distribution of annual average daily PET values for the period 1981–2021 in Iraq

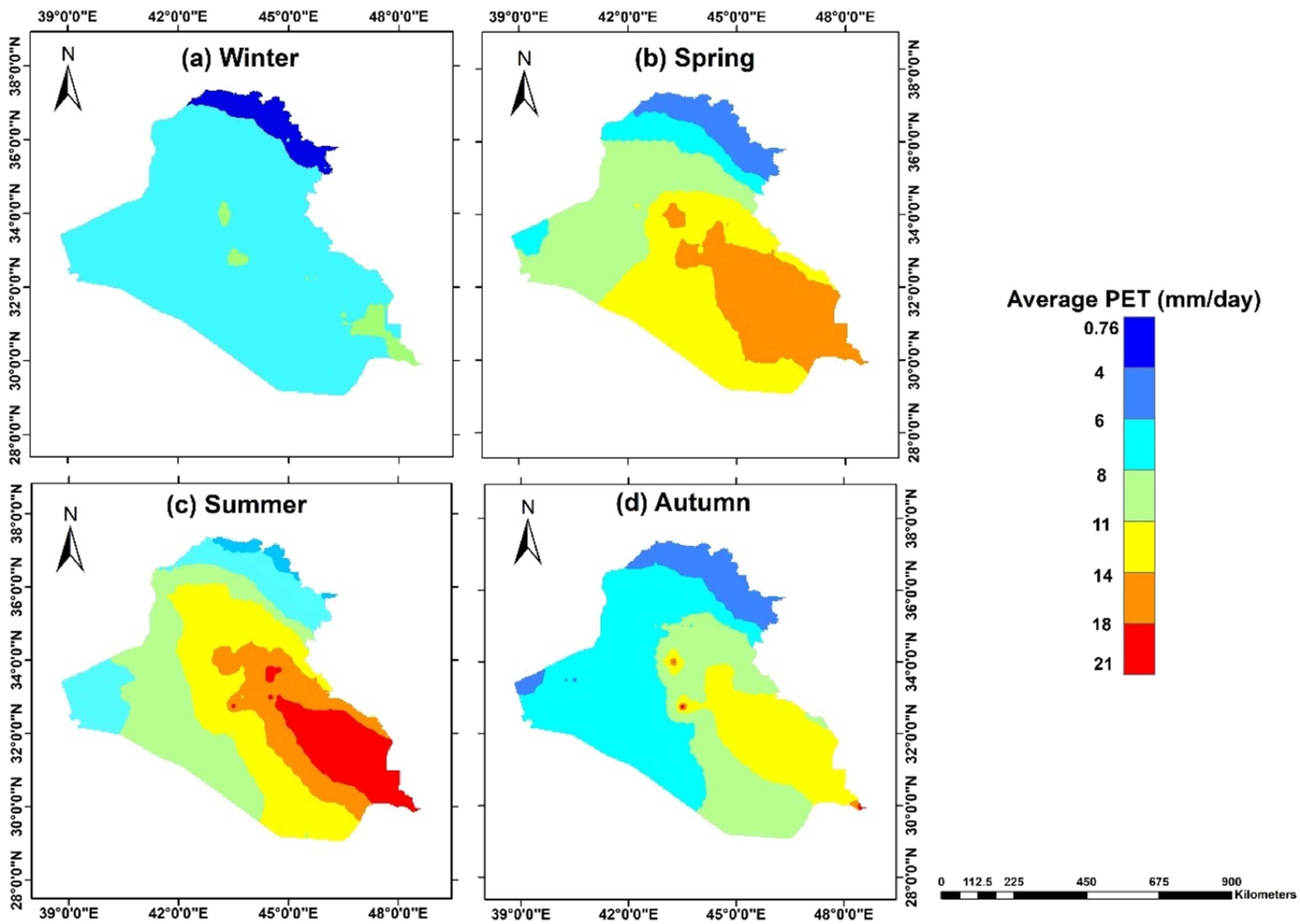


Fig. 3 Spatial distribution of average daily PET in (**a**) winter, (**b**) spring, (**c**) summer, and (**d**) autumn for the period 1981–2021 in Iraq

Figure 2 clearly shows that for annual PET, a considerable portion of northern Iraq had an average PET between 3.0 and 7.3 mm/day. The figure also shows that the average PET was 6.0−8.4, 8.5−10.0, and 11.0−14.0 mm/day in Iraq's western, central, and southern parts, respectively. Thus, the annual average daily PET values varied from 0.76 to 7.0 mm in the north and west and 11.0–18.0 mm in the south and southeast Iraq. Figure 3 reveals that for seasonal PET, the obtained results showed that the lowest average PET values were 0.76–6.4 mm/day during winter. The average PET values were 3.3–14.0 mm/day in autumn and 1.9−11.0 mm/day in spring. However, the highest average PET values were 6.0–21.0 mm/day during the dry summer. It is worth mentioning that the main reason for the relatively high values of PET in the southern of the country during summer is due to its arid and semi-arid climate, which is associated with high temperatures and evaporation rates. The overall pattern of PET change in different regions of Iraq remains consistent from season to season, i.e., the average daily PET values in the north and west of the country are generally lower than the average daily PET values in the southern and southeastern regions.

Figure 4 illustrates the spatial patterns of estimated monthly mean PET values from 1981 to 2021. The results demonstrated that the monthly average PET values, interpolated by the IDW method, have been divided into seven classes ranging from 0.52 to 30.0 mm/day. The lowest values of PET average were found in November, December, January, and February, whereas the highest average values occurred in May, June, July, and August. In general, the obtained results reflected the dominant climate type of each region, which was considered a Mediterranean climate in the northern and northeastern parts and a continental arid and semi-arid type in central and southern Iraq. Interestingly, spatial pattern maps showed that Al-Tharthar Depression and Al-Razzaza Lake, located in the central-western part of Iraq, had comparatively high PET values for all months and seasons (Figs. 3 and 4). It might be due to the relatively high evaporation rates in these two water lakes compared to the surrounding areas that are commonly arid and semi-arid and often associated with high temperatures and evaporation. It represents a significant result because it indicates that the atmospheric water loss is high in the arid region of Iraq. In short, the monthly average daily PET has almost the

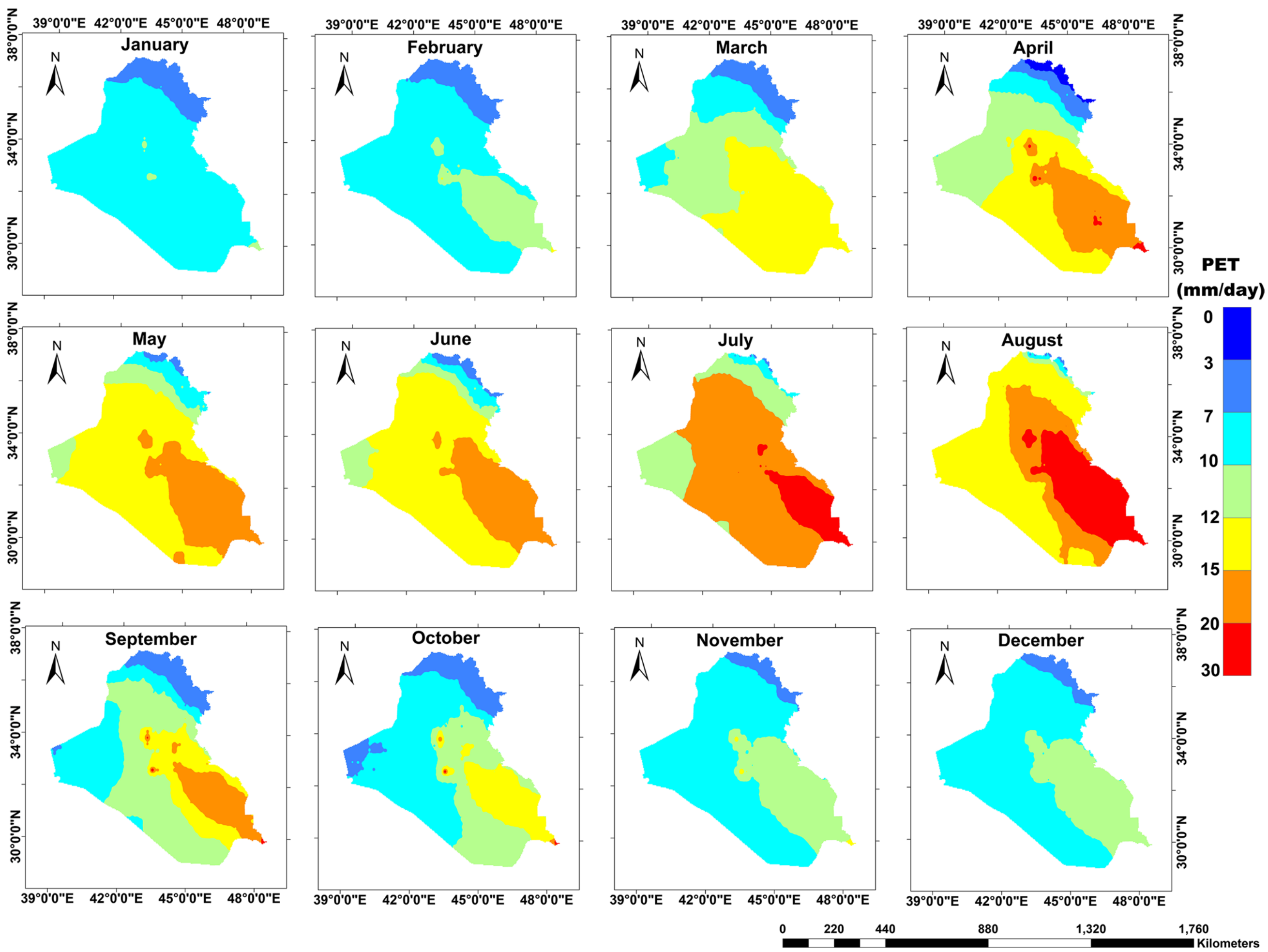


Fig. 4 Spatial distribution of average PET in mm/day in different months of a year for the period 1981–2021 in Iraq

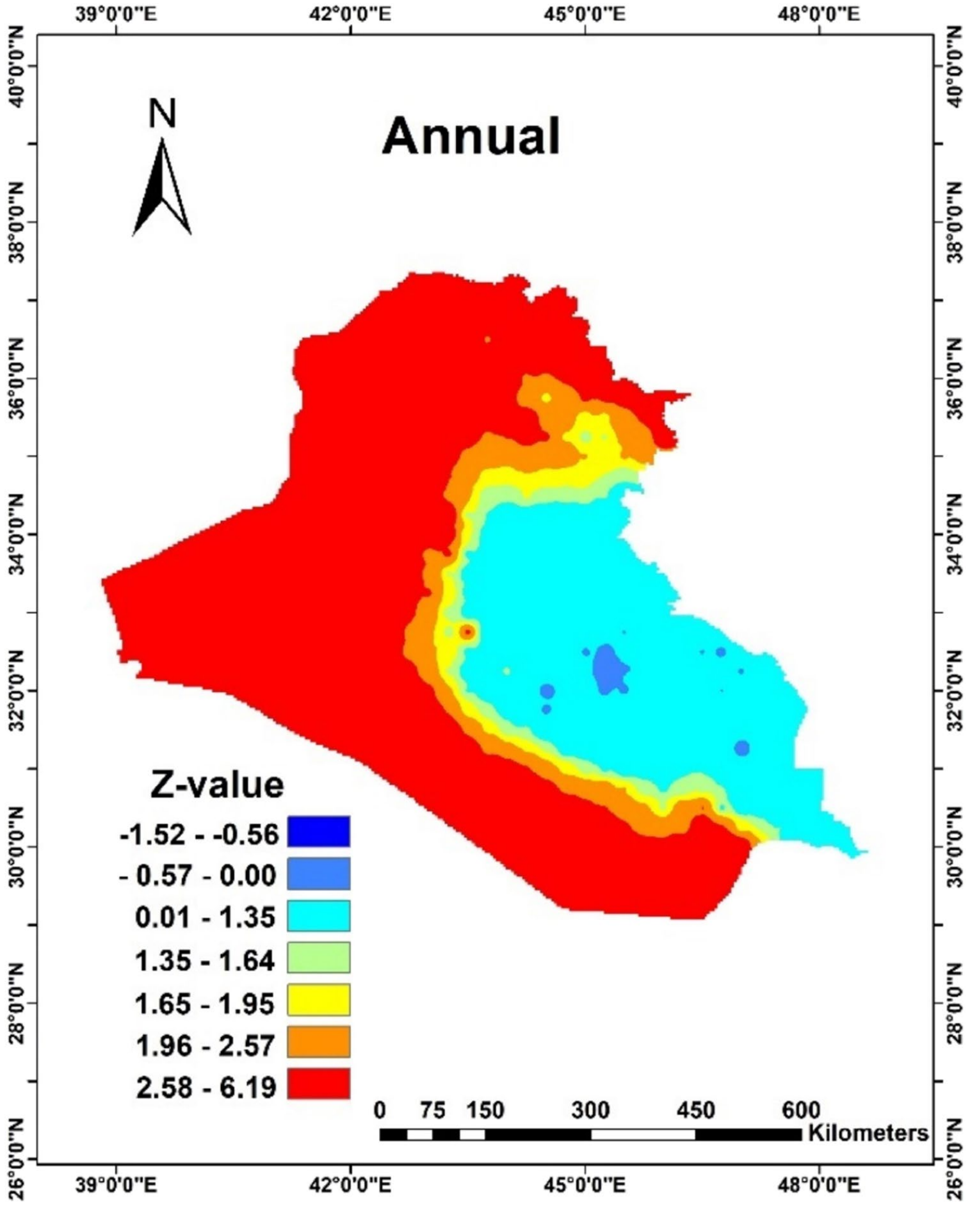
same patterns as the seasonal average daily PET, i.e., the average PET values that occurred during the winter months are lower than the average PET values detected during the summer months.

3.2 Trends in annual and seasonal potential evapotranspiration series

Trend significance of the annual and seasonal PET time series at all grid points in Iraq was estimated using the MMK trend test. Figures 5 and 6 demonstrate the spatial distribution patterns in the *Z* (MMK) statistics for annual and seasonal PET from 1981 to 2021. The results exhibited a statistically significant increasing trend for annual PET time series noted for all the regions of Iraq, except the eastern and southeastern Iraq, over the past four decades at 95% and 99% confidence levels. Figure 5 shows that there has been a significant positive trend for annual PET detected in the north, northeast, northwest, west, south, and southwest of the country, with a *Z* value in the range of 2.58 to 6.19, indicating a significant trend at 99% confidence interval. A similar significant change in the annual PET was also noticeable in the borders of the alluvial plain of Iraq, with a *Z* value ranging from 1.96 to 2.57 for the MMK test (95% confidence level). In addition, trends of annual PET were statistically non-significant for the Iraqi alluvial plain, i.e., covering a considerable portion of areas located in the east, central, and southeast of Iraq, with a *Z* value that lies within the range of 0.0 to 1.64 for the MMK test. However, only a few randomly distributed grid cells in the southeastern region had a statistically insignificant negative annual trend, with a *Z* value of − 0.01 to − 1.52 (Fig. 5). Overall, the PET time series showed a significant positive trend in northern, northeastern, northwestern, western, southern, and southwestern parts of Iraq. The presented results imply that the annual PET rising trends detected by the MMK test can be related to the influence of the unidirectional trends caused by global climate change.

The results of seasonal trends analysis revealed that the winter PET had experienced significant upward trends in

Fig. 5 Spatial distribution of the modified Mann–Kendall *z*-statistics of annual PET from 1981 to 2021 in Iraq. The *z*-statistics 1.65–1.95 denote significant change at 0.10 confidence level, 1.96–2.57 denote significant change at 0.05 confidence level, and ≤ 2.58 denote significant change at 0.01 confidence level



almost all grid points in Iraq using the MMK test at 95% and 99% confidence intervals. Figure 6 demonstrates that a small portion of eastern Iraq had a trend in winter with a *Z* value ranging from 1.64 to 1.95. It implies that winter PET has changed notably over the past 40 years. The figure also shows that the spring PET time series had statistically significant positive change detected at all the grid points in the study area at 99% confidence levels, except the alluvial plain of Iraq. The region of the alluvial plain had a weak positive trend, obtaining a *Z* value range from 1.35 to 1.95. Besides, the summer and autumn PET series had increasing trends in northern, western, and southwestern Iraq. Unlike winter and spring PET, summer and autumn PET trends were negative and statistically insignificant for some parts of the Iraqi alluvial plain, with a *Z* value ranging from − 0.56 to − 1.52. Although the trends of all seasons, except winter, were non-significant for the Iraqi alluvial plain covering most of the eastern and southeastern parts of the country, there was a significant positive trend in the long-term seasonal PET detected in other Iraqi regions. Therefore, the attained results revealed that the atmospheric water demand measured by PET is risen rapidly over the past four decades, representing a clear indication of global climate change effects in this region.

3.3 Spatial patterns in the trend magnitude of annual and seasonal PET

Figures 7 and 8 show the results of the spatial distribution patterns of the changes in Q_i average values of Sen's slope

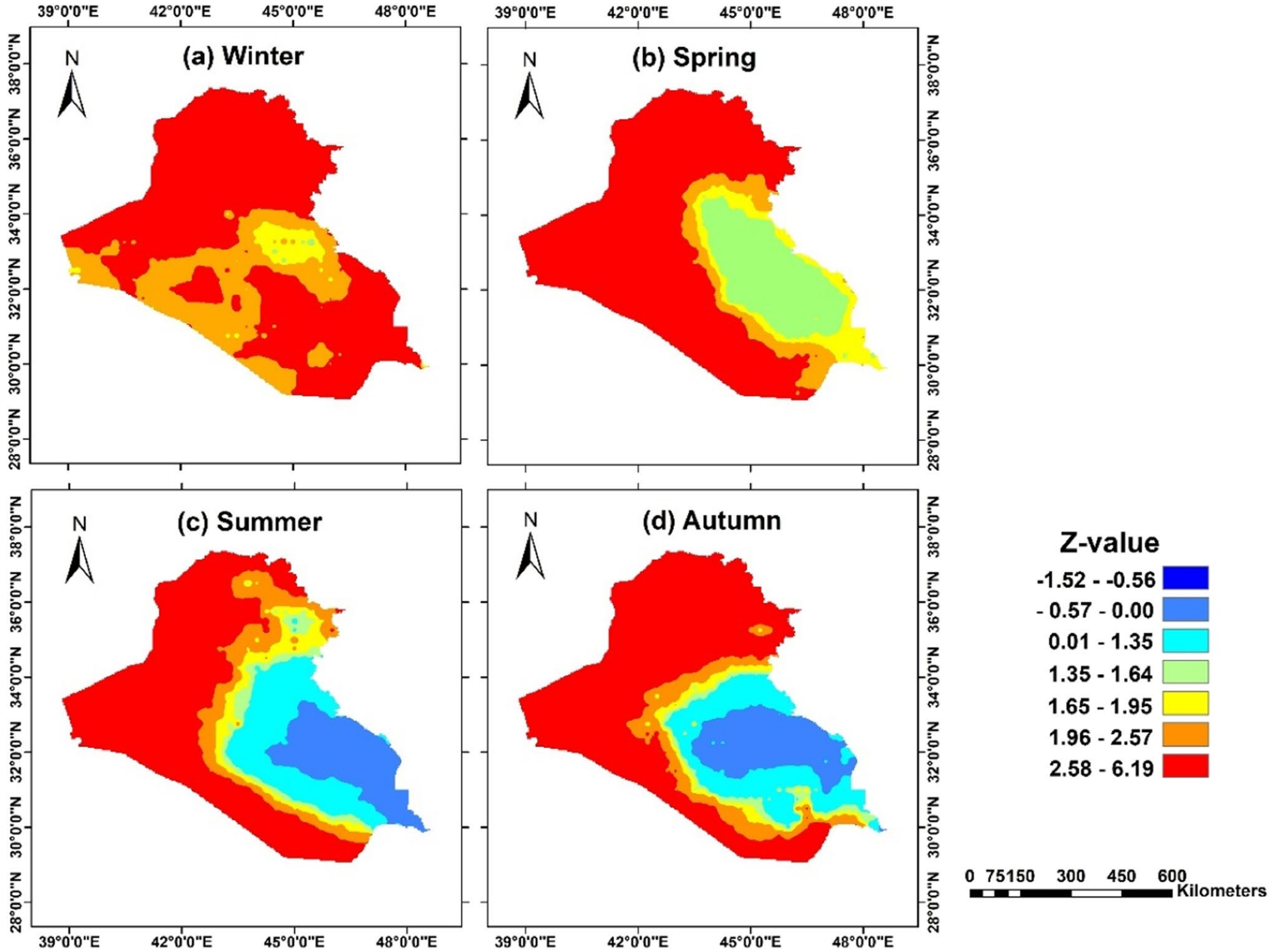


Fig. 6 Spatial distribution of the modified Mann–Kendall z-statistics of (**a**) winter, (**b**) spring, (**c**) summer, and (**d**) autumn PET from 1981 to 2021 in Iraq. The z-statistics 1.65–1.95 denote significant change at 0.10 confidence level, 1.96–2.57 denote significant change at 0.05 confidence level, and ≤ 2.58 denote significant change at 0.01 confidence level

estimator for the annual and seasonal PET trends from 1981 to 2021 in Iraq. The results demonstrated an overall positive trend observed in the annual time series for most grid cells in Iraq over the past 40 years. The trend magnitude of the detected increasing annual PET average values was primarily high, with Q_i ranging from 0.0013 to 0.065 mm/year for the north, northwest, west, and southwest regions. Nonetheless, it was either relatively low or negative, with Q_i ranging from 0.0081 to − 0.0018 mm/year for the eastern and southeastern parts of the country (Fig. 7). It is valid to mention that the trend magnitude of mean annual PET has almost the same patterns as the trend significance of mean annual PET. However, the highest Q_i values were observed in the Iraqi desert in the southwestern part, close to the Iraq-Saudi Arabia borders and a part of the Arabian desert, with a Q_i ranges between 0.028 and 0.065 mm/year (Fig. 7). Accordingly, the magnitude of trends for annual PET showed a general increasing tendency for all the grid points in the study area, except the alluvial plain covering a large portion of eastern and southeastern Iraq.

Analyzing seasonal trends magnitude showed that the amount of trend change was relatively low in the winter series, with a Q_i ranging from 0.018 to − 0.008 mm/year. However, the rate of magnitude was negative (− 0.0018 to − 0.0019 mm/year) for grid points generally located in the middle and Mideastern Iraq. Figure 8 reveals that in the spring series, PET trends magnitude had an increasing rate for all the country, with a positive rate ranging from 0.008 to − 0.065 mm/year. In summer, Q_i values had the highest increasing trend magnitude compared to other seasons in northern, northeastern, western, and southwestern Iraq (Fig. 8). The results demonstrated that the Q_i values increased rapidly throughout summer, with 0.035 to 0.065 mm/year. It indicates that the PET during summer has changed significantly over the past 40 years in these regions of Iraq. Also, summer

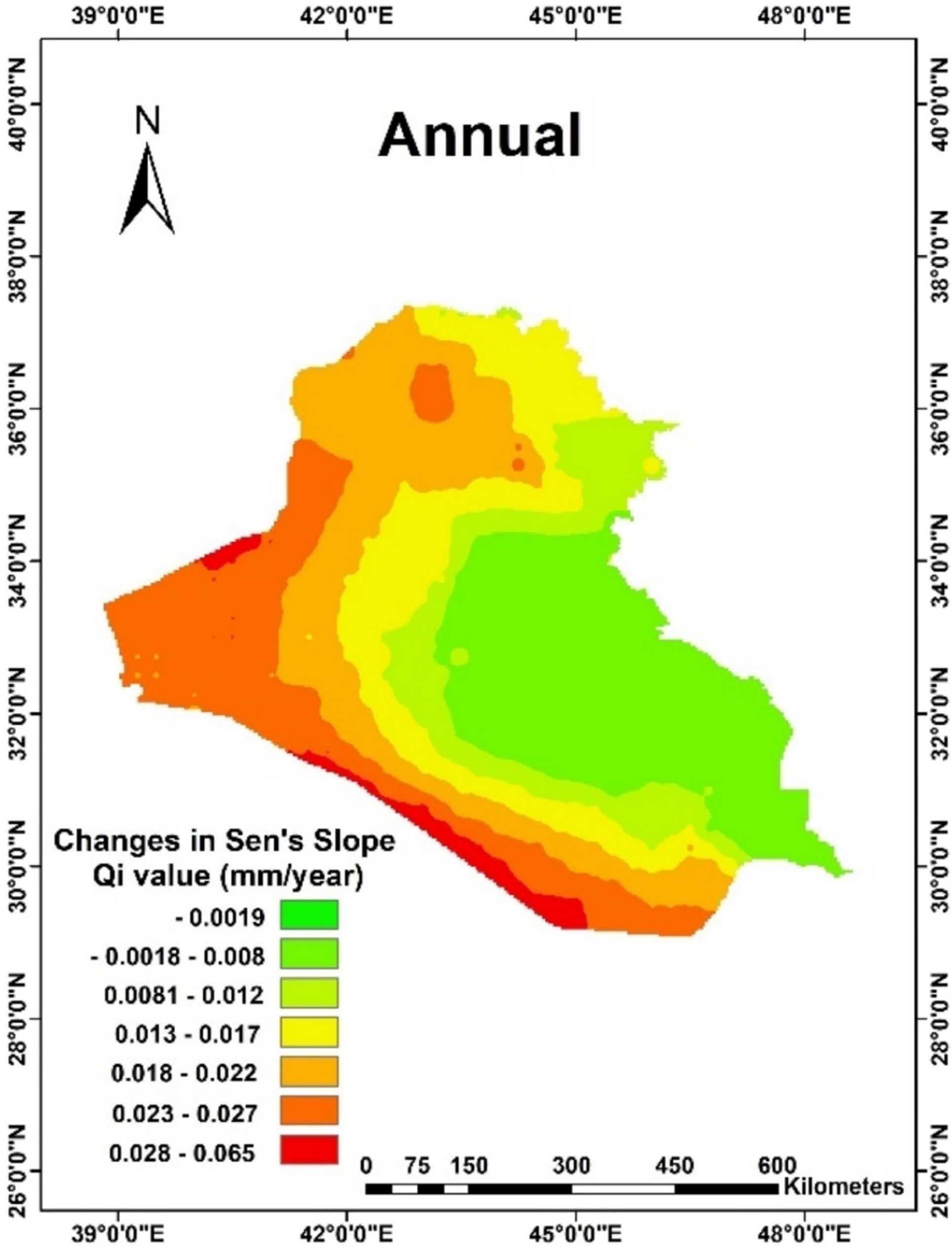


Fig. 7 The spatial distribution of the changes in annual PET during 1981–2021 in Iraq. The negative (positive) sign denotes a significant decrease (increase) in PET

had the highest trend magnitude and contributed considerably to the significant changes in annual PET. For autumn PET, the statistic values of Q_i were high (0.0017 to 0.065 mm/year) in northern, northwestern, western, and along the international border of southwestern Iraq but negative at a small number of grid cells situated in eastern and southeast. The mean PET showed an upward trend at annual and seasonal scales. However, summer had the highest increasing trend magnitude of 0.35 to 0.65 mm/decade, followed by spring, autumn, annual, and winter. Thus, a rapidly rising PET trend was observed clearly in all seasons and many parts of Iraq over the last four decades.

3.4 Relationship between potential evapotranspiration and climatic parameters

For studying the main climatic parameters affecting the PET in each grid point of different Iraqi regions, the Pearson's correlation coefficient between PET and various meteorological factors utilized to estimate PET in each grid point was computed. Figure 9 shows the spatial distribution of Pearson's correlation coefficient (r) between PET obtained using the FAO P-M method and various climatic factors, i.e., net SR, AT, atmospheric surface pressure, and WS, from 1981 to 2021. The figure shows that SR and

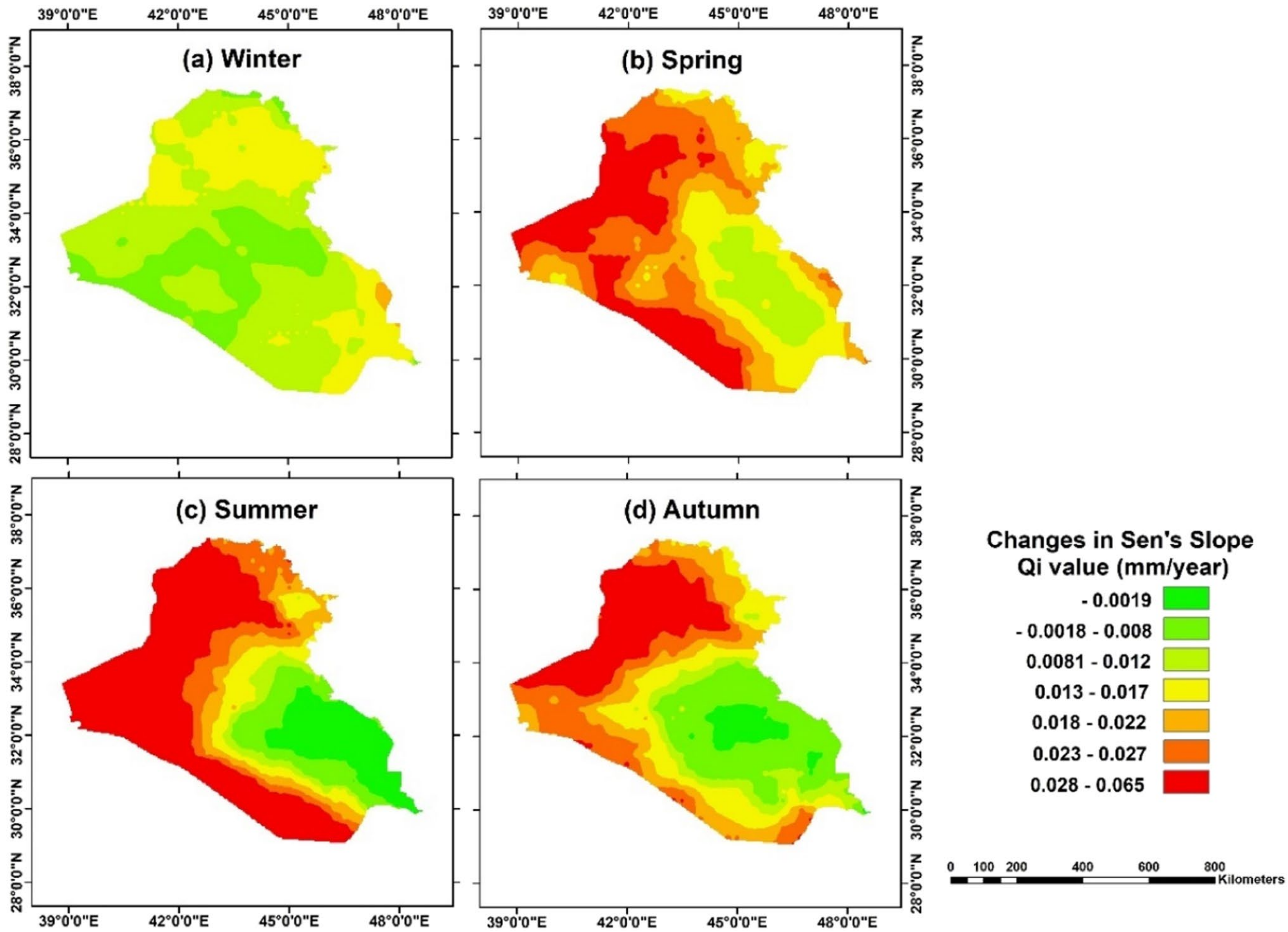


Fig. 8 The spatial distribution of the changes in PET for (**a**) winter, (**b**) spring, (**c**) summer, and (**d**) autumn during 1981–2021 in Iraq. The negative (positive) sign denotes a significant decrease (increase) in PET

AT were positively correlated with PET, while ATP and WS were correlated reversely with PET. For AT, spatial correlation analysis indicated a strong positive correlation between AT and PET, with Pearson *r* ranging between 0.77 and 0.88 detected for the central, southern, and northwestern regions. In addition, the Pearson's coefficient values also demonstrated a strong positive correlation between PET and SR; however, it was comparatively lower than the relationship of the AT, with a Pearson's *r* value in between the range of 0.50 to 0.83. Besides, the obtained results of spatial correlation demonstrated that the estimated Pearson's *r* value was from 0.14 to – 0.87 and from – 0.21 to 0.58 for ATP and WS, respectively. Results found that even though ATP and WS had a negative relationship with PET, they exhibited positive relationships in some grid points distributed in a few regions (Fig. 9c and d). For ATP, all detected positive Pearson's *r* values were in a few grid points in the northeastern mountainous region; however, the highest observed negative values were in the south and central part of Iraq. It can be attributable to the low elevation close to sea level and the arid and semiarid climate influencing the region. WS, however, explored some positive correlations dispersed over different grid cells of the country. The spatial distribution of *r* values of WS revealed the highest number of positive values concentrated in the line starched from northwest to southeast. It represents an important finding for the study area because the highest WS values were in these parts of Iraq, particularly in grid points located in Al-Nasiriya and Wasit provinces in south and southeast Iraq. In short, the most notable finding for the study area based on spatial correlation analysis was the strong correlation between AT and PET. Therefore, the AT appears to be the most controlling meteorological parameter to the rising PET across central, southern, and northwestern regions.

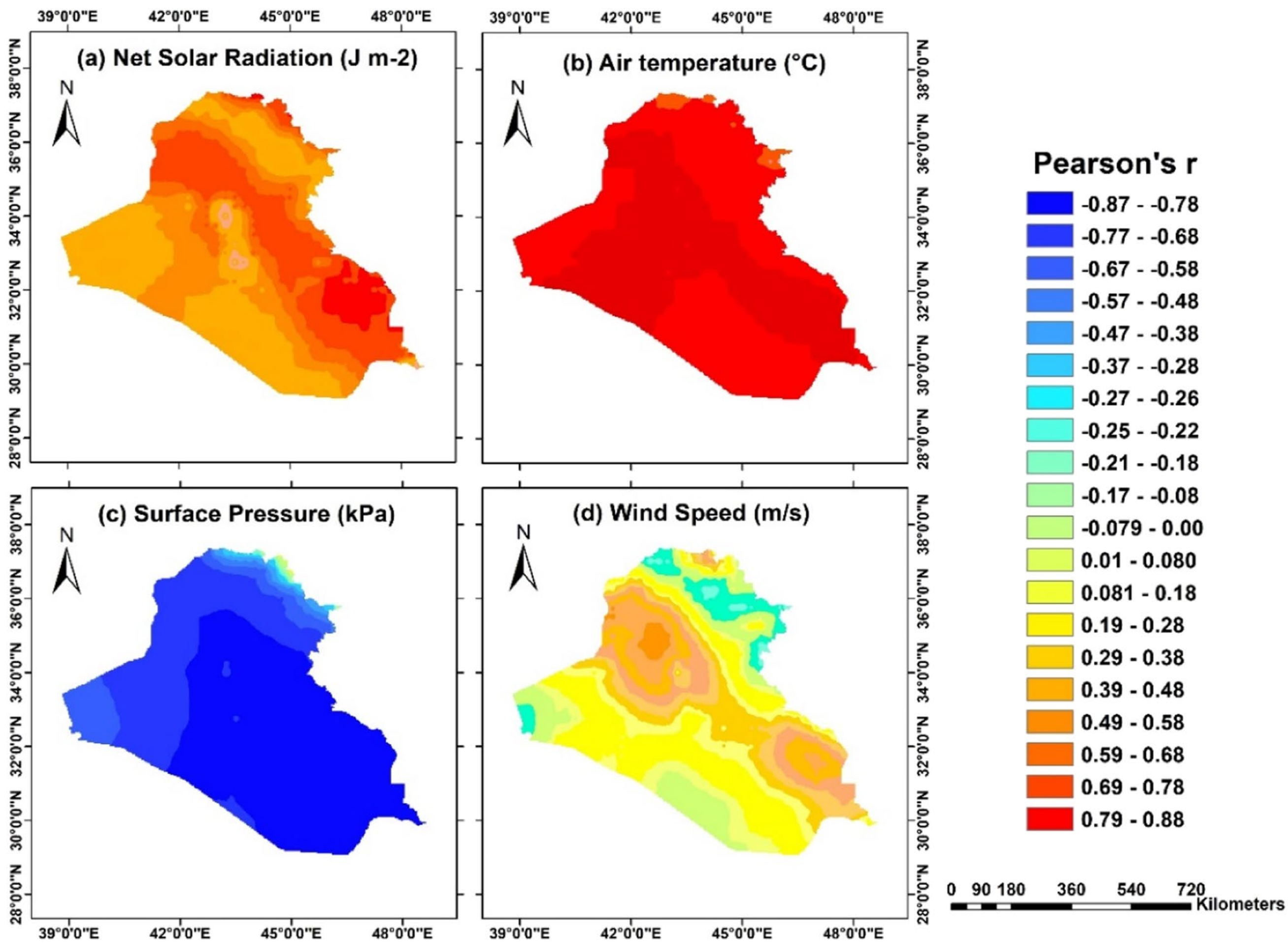


Fig. 9 Spatial distribution of Pearson's correlation coefficient (*r*) between PET, estimated using the FAO P-M method, and different climatic factors: (**a**) net solar radiation, (**b**) air temperature, (**c**) surface pressure, and (**d**) wind speed during the period 1981–2021 in Iraq

3.5 Spatial distribution of climatic factors contribution rate to the PET

For elucidating the climatic factors controlling the increase in PET trend, the spatial distribution of different climatic variables, namely AT, net SR, WS, and ATP, was assessed. The contribution rate of each climatic variable, which indicates how the change of the variable variations PET, was estimated to identify the dominant climatic variable of PET. Figure 10 illustrates the spatial distribution of contribution rates of main climatic parameters to PET from 1981 to 2021. The figure clearly shows that the contribution percentage of each climate variable varied spatially over various regions, which was measured using the linear regression method. The figure also illustrates the influence of AT, SR, ATP, and WS on PET values. It was between 26 and 93.5%, 3.4 and 10.9%, – 0.08 and – 0.54%, and 70 and – 59.5%, respectively. Results showed that AT is the main positive contributor to the increase in PET in different parts of Iraq.

Results indicated that the positive influencing climatic factors, including AT and SR, were attributed primarily to the increasing trend in PET. Results demonstrated that AT was the most significant climate variable for the detected increasing trend in PET, with the most influence in Nineveh, Saladin, Baghdad, Wasit, Maysan, and Basra Provinces in central and southern, and northwestern regions (Fig. 10b). Although SR had a less positive contribution to the observed rising PET, it had almost the same distribution patterns in influence as AT (Fig. 10a). The negative factors such as ATP and WS were largely correlated with PET in the study area. However, they had a negligible effect on the observed PET, particularly atmospheric surface pressure, due to the small influence on total estimated PET, except for the southeastern region in Maysan and Basra Provinces, as shown in Fig. 10c. A general reverse correlation has identified for WS in different areas, as shown in Fig. 10d. However, the negative contribution of WS and surface pressure decreasing to PET remained offset by AT and SR. It is worth noting that WS was correlated positively in Erbil, Sulaymaniyah, Duhok,

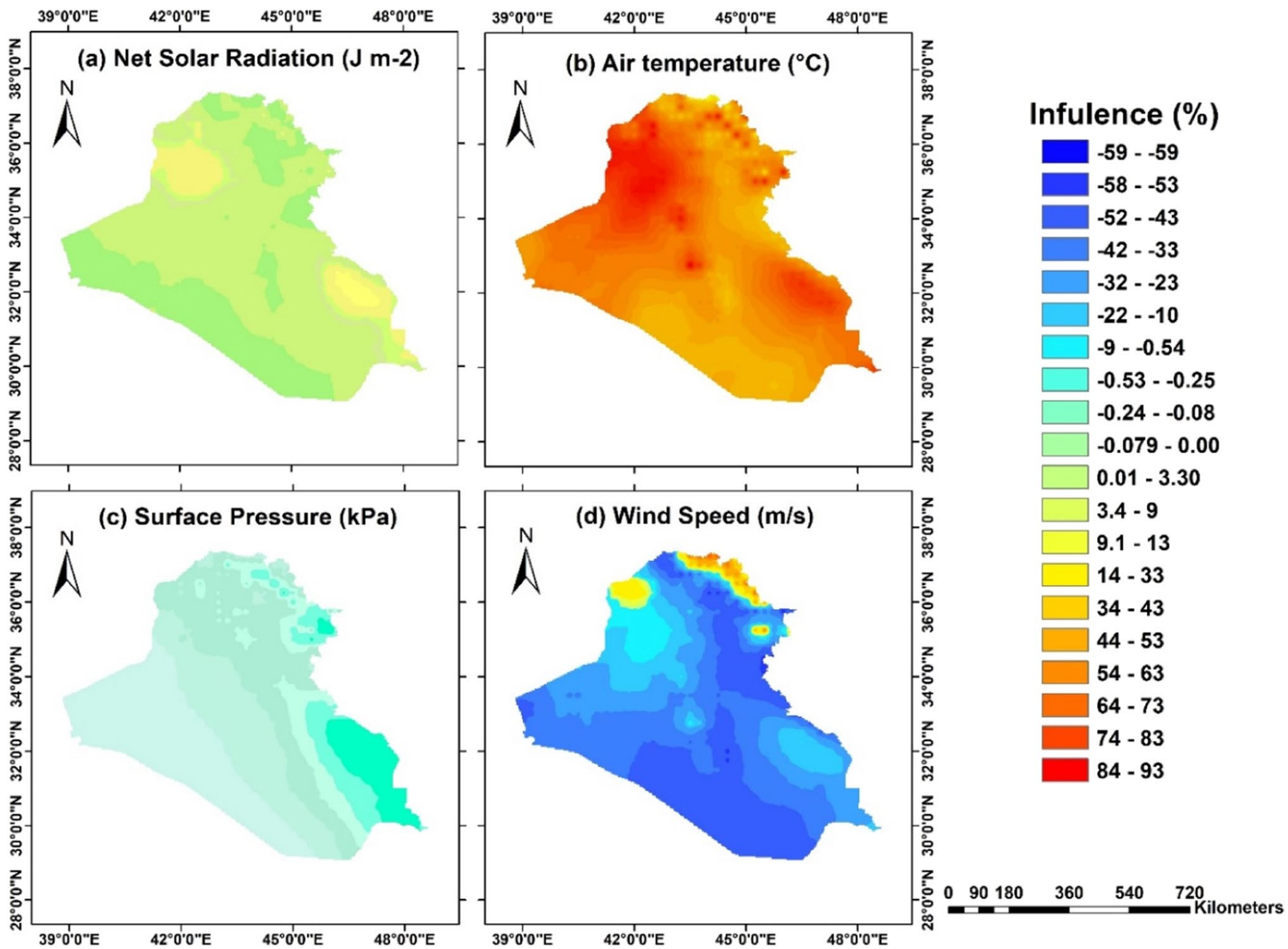


Fig. 10 Spatial distribution of the contribution of different climatic factors to the changes in PET: (**a**) net solar radiation, (**b**) air temperature, (**c**) surface pressure, and (**d**) wind speed for the period 1981–2021 in Iraq

and Nineveh provinces, i.e., areas mainly situated in the mountainous ranges of northern Iraq. Besides, the WS was the most controlling climatic variable in the observed PET in Najaf, Muthanna, Diyala, Saladin, and Kirkuk provinces located in the southwestern and eastern parts of the country (Fig. 10d). Overall, it is valid to state that the increase in PET is driven primarily by AT and, to a lesser extent, SR; in comparison, the observed insignificant decrease is by WS and ATP. Therefore, rising AT caused by global warming is the primary cause of PET variations in Iraq.

4 Discussions

The present paper addresses the clear knowledge gap for comprehensive spatial trend analysis research in PET and the influencing driving climate factors for the changes in PET at annual and seasonal scales in Iraq. Therefore, this study aimed to estimate the daily PET values for all the Iraqi lands using the FAO P-M method, analyze the significant gradual trends in annual and seasonal PET, and detect the controlling climatic factors for spatial distribution fluctuations in the PET series of the considered region of Iraq. The changes in PET were studied using the latest European reanalyzed ERA5 data from 1981 to 2021 for each grid cell inside the Iraqi territory. Different statistical methods (i.e., parametric and nonparametric) were employed to assess the spatial changes in the estimated PET at the annual and seasonal timescales. They can consider the influence of autocorrelation in the PET time series and identify the driving influencing variables for PET alterations, as discussed in the following subsections.

Obtained results showed that the estimated long-term annual and seasonal PET had increased considerably, during the last 40 years, for all the considered regions, except the Iraqi alluvial plain of Tigris and Euphrates rivers covering the eastern and southeastern parts of Iraq. The results indicated that there had been a significant increasing trend for annual PET observed in the north, northeast, northwest, west, south, and southwest of the country at the 5% and

1% significance levels. Trend significance of the annual and seasonal PET time series at all grid points in Iraq was estimated using the MMK trend test. There have been prominent variations in the spatial distribution patterns of the Z (MMK) statistics for annual and seasonal PET from 1981 to 2021. Overall, the PET time series showed a significant positive trend in all the Iraqi lands, except the alluvial plain of Iraq, at annual and seasonal scales, with a Z value ranging from 1.96 to 6.19 for the MMK test at 95% and 99% confidence levels. The results revealed a high level of PET rising trends identified for these parts of the country because of the large Z values (2.58 to 6.19) for the MMK trend test. Since the MMK test can separate the trends caused due to natural variability of climate, the detected increasing PET trends in this study by the MMK reported in most parts of Iraq can be linked to the unidirectional trends caused by climate change in those regions. It represents an important finding raised for the study area of Iraq, as it has not been reported previously in the literature. This result is especially true for Iraq because knowledge about the fluctuations in the PET trend and its influencing atmospheric variables based on the MMK test is quite limited. Accordingly, it was impossible to compare the attained results of this study with the available literature.

On the other hand, the Iraqi alluvial plain, extending for a large portion of areas in the east, central, and southeast of Iraq, exhibited a statistically insignificant positive trend, with a Z value ranging from 0.0 to 1.64 for the MMK test. Since the MMK test can distinguish the variables caused by natural variability from the unidirectional trends of climate change, the detected increasing trends in this study by the MMK test are linked mainly to impacts of climate change in the region. Therefore, it has indicated that the key reason for the variations in the spatial distribution of the MMK z-statistics is the unidirectional trends caused by global climate change.

Only the winter PET series had shown significant rising trends in almost all grid points in Iraq using the MMK test at the 5% and 1% significance levels. However, the annual, summer, spring, and autumn PET series had nearly the same distribution patterns, i.e., the PET series had statistically significant positive change identified for all the grid points in the study area using the MMK test at 95% and 99% confidence interval, except the alluvial plain of Iraq. More importantly, the spatial distribution results of trend magnitude assessed by Sen's slope estimator confirmed the detected trend significance results, which have almost the same patterns as the trend significance of mean annual and seasonal PET. The Q_i of Sen's slope had the highest values in the Iraqi desert in the southwestern part, with a Q_i value range between (0.28 and 0.65 mm/decade). This result is not surprising because the Iraqi desert, a part of the Arabian desert, has a dry and hot climate for most of the year. The temperature in the region often reaches more than 50 °C during summer based on the records of temperature highs in Iraq. Results also suggest that summer had the highest rising trend magnitude (0.35 and 0.65 mm/decade), followed by spring, autumn, annual, and winter. Accordingly, the attained results demonstrate that the annual and seasonal PET that denotes a measure of atmospheric water loss is escalated considerably throughout the past four decades in Iraq, which shows a direct indication of the impacts of climate change in the region.

The attained results of the daily PET in this study using the FAO P-M method have several advantages. First, the FAO P-M method is not only the standard method for calculating PET (Allen et al. 1998; Muhammad et al. 2019), but also it provides more accurate results for numerous regions, including arid and semi-arid. Second, the FAO P-M combination-based methods are considered more robust and consistent than temperature-based, mass-transfer-based, and radiation-based methods. Third, it had recommended by the FAO organization to be used fundamentally for PET estimation (Allen et al. 1998). However, the main limitation of employing this method in all regions is the need for several climatic data (i.e., AT, DT, WS, ATP, and surface total SR), which are not always available for the long-term record in data-scarce regions like Iraq. This limitation had addressed by adopting the newest global ERA5-Land dataset. Thus, it represents the first detailed study to estimate PET using the standard FAO method in Iraq.

The findings of this research concur partially with the results of other studies conducted in neighboring countries bordering Iraq and the Middle Eastern region about the variations in PET. Dinpashoh et al. (2019) analyzed the annual and monthly PET for 36 synoptic stations in different periods in the west and northwest of Iran, which found that PET estimated using the FAO P-M method had an upward trend for most of the considered stations in Iran. Collins et al. (2021) studied the changes in PET at spatial and temporal scales from 1957 to 2016 using CRU TS gridded data in Iran. They stated that the annual PET and the reference crop water requirement had an increasing trend in the area extending from the northeast to the southwest. In contrast, a decreasing trend was identified for the southeast of Iran. On a seasonal scale, the highest rising in PET was observed in spring and summer. Accordingly, other works carried out in the Middle East, such as the previous work by Dinpashoh et al. (2019) and Collins et al. (2021) in Iran, are consistent with the outcomes of this study.

The results showed that AT was the main contributor to the detected increasing trend in PET. The results revealed a strong spatial correlation between AT and the estimated PET, as indicated by the Pearson r ranging from 0.77 to 0.88. It was also consistent with the attained results of the contribution analysis of climatic variables to the rising PET.

The AT's contribution to the increasing PET was between 26 and 94%, indicating the highest contribution percentage detected in the central, southern, and northwestern regions. As a result, the significant increase in PET over the Iraqi land can be linked directly to the fast rise in AT in Iraq. This finding was in line with the observed general positive trend in AT in Iraq. The literature suggests that the temperature in the country is rising drastically within the range of 2 to 7 times faster than the global average temperature increase (Salman et al. 2017). Also, it concurred greatly with the outcomes of several previous studies that reported a high level of warming trends identified in many parts of the country (Robaa and Al-Barazanji 2015; Al-Hasani 2021). Generally speaking, the global warming phenomenon had reported to severely affect the regions of arid climate zone compared to other climate types (Ahmed et al. 2016; Nashwan et al. 2020). The increasing warming trend is likely to be increased in the coming years. It had noted that temperature will rise in a range of 0.8–3 °C from 2020 to 2079 compared to the base period (1985–2014) in the Middle East and North Africa region (Majdi et al. 2022). Accordingly, the increase in PET is attributable to the continuous rise in AT, which is most likely to further intensified in the short and long-term future. The general variations in AT can lead to notable changes in the saturation vapor pressure. Hence, it can alter the evaporation and PET (Dinpashoh et al. 2011). Yet, the influence of such change on PET is complicated and often difficult to quantify because any change in a variable may result in a direct or indirect alternation in other variables. Although there is a large diversity of climatic conditions in different regions of Iraq, the At is the primary driver of PET's significant spatial changes. It is expected that with the global mean temperature rise, the spatial patterns of the PET will continue to change significantly in Iraq. The attained results found that the annual and seasonal PET had increased in most Iraqi lands, and its patterns mostly correlated with At. Therefore, it is valid to report that one of the most important findings of this paper is that At is the most dominant parameter influencing PET in almost all Iraqi land.

The spatial distribution maps showed that Al-Tharthar Depression and Al-Razzaza Lake, located in the central-western part of Iraq, had the highest PET values for all months and seasons (Figs. 2, 3, and 4). The main reason for the relatively high evaporation rates in these two water sources was the climate of this area, which is mainly classified as arid and semi-arid and often associated with high temperatures and evaporation. Results indicated that AT was the primary influencing climatic parameter on PET in middle-western Iraq, followed by SR and WS. The AT was responsible for 86.7% and 93.5% of the observed rising trend in PET for the Al-Tharthar and Al-Razzaza Lakes. Nevertheless, SR contributed to the positive increasing trend in PET estimated for Al-Tharthar and Al-Razzaza Lakes by 5.7% and 6.3%, respectively. It means that AT accounts for more than 90% of the detected upward trend of PET in these two vital water reservoirs in Iraq. Since 1956, the Tharthar Depression, which is linked to the Euphrates and Tigris Rivers by controlling canals, has been used as an artificial reservoir (length of 120 km and width of 45 km) to regulate the flow of the Tigris River by diverting excess water of the river during the flooding seasons via the Tharthar Canal. The diverted water has helped to effectively minimize the flood risk threatening Baghdad city and reused it throughout the drought season. As a result, the Tharthar project represents one of the substantial components of the Iraqi water resources management system since completed in 1977 (Al-Ansari et al. 2018). Thus, the significant atmospheric water vapor loss from those largest surface water bodies in the country through the detected increasing PET rates and its effects on salinity levels in lakes under semi-arid and arid conditions should be considered in water resources planning in Iraq. With expected continuous increasing PET in Iraq and the reduction of supplying surface environmental water to lakes and wetlands, most water bodies will likely disappear, especially in the small Mesopotamian Marshlands in the southern region. Overall, this appears to be a significant finding in the study region, as it does not mention, so far, in any previous study.

Moreover, the results revealed that WS was correlated significantly with the PET in northern Iraq. A strong correlation between WS and PET was detected, with the Pearson r ranging from − 0.21 to 0.58 and a contribution of 70 to − 59.5%. The highest negative attribution rate identified for different grid cells starched from the northeast to southwest. In contrast, the highest positive contribution percentage was in grid cells distributed from the northwest to the southeast part of Iraq. Hamadamin et al. (2021) also reported similar significant positive and negative trends in the annual PET computed using the FAO-PM method at spatial and temporal time scales in the northern region of Iraq. They found that WS was the main influencing factor in PET in the north of the country, which is consistent mainly with the finding of the present paper. It is important to note that the paradox phenomenon distinguished by PET change does not exist in Iraq. In general, evaporation from soil and water bodies is most likely to increase as the mean global temperature rises. However, the observed evapotranspiration across different regions exhibits a downward trend commonly known as the paradox (Roderick and Farquhar 2002). Thus, based on the obtained results of this study, the paradox phenomenon in Iraq is not applicable, and further investigations need to be applied to confirm this finding. It is a notable finding of the present study, as it has not been discussed previously in the literature for the study area.

Along with temperature and precipitation, PET is a significant climatic parameter commonly used to assess the effects of climate change on the hydrological cycle. Changes in the main characteristics of PET can influence the precipitation patterns, terrestrial water fluxes, soil moisture, groundwater storage, surface runoff, and consequently, the hydrological cycle, which in turn may affect the crops (Singer et al. 2021). Water resources and agriculture in Iraq would be among the most affected sectors by the rising PET. Iraq is considered an agricultural country where the rural population, especially small-scale farmers, relies mainly on agriculture for their needs and living. Agriculture is the major consumer of surface water and is primarily irrigated, particularly in the Iraqi alluvial plain between the Tigris and Euphrates rivers in the central and southern regions of the country. However, most of the agricultural region in the north is rainfed, where rainfall is within the range between (250 and 400) mm. The results of this study show that the significant increasing PET trends estimated by the MMK test at the annual and seasonal scales are noticeable in the northern rainfed region. The attained results of the trend magnitude of average annual and seasonal PET confirmed the trend significance in this region, with a *Qi* value ranging from 0.012 to 0.065 (mm/year). It suggests that the main characteristics of the hydrological cycle might be affected by the observed rising PET trends. In addition, the increasing PET has already increased the water vapor demand in the atmosphere. Accordingly, it can lead to a considerable increase in crop water demand and a decline in climatic water availability. Crop water requirement is most likely to increase in irrigated arid and semiarid areas, generally concentrated in the central and southern regions of the country. The results also showed that the increasing temperature has changed the PET in Iraq, which is more likely to continue because of the constant rising trends in mean temperatures. It can, thus, result in variations in water availability and increased crop irrigation requirements in the region. Therefore, analyzing the alterations in the characteristics of PET in this study is not imperative for generating immediate measures to address the challenges of water resources and agriculture but also fundamental for such a highly vulnerable country to global climate change as Iraq. Overall, the obtained results can be helpful for climate change adaptation and mitigation plans for water resources and agriculture in Iraq.

The study did not analyze the relationship between botanical or hydrological influences on the spatial distribution of the detected increasing trends of PET due to the lack of the required data for the study area. Accordingly, it was beyond the scope of this study. Besides, the effects of some notable factors such as land use, precipitation, and vegetation and its complex feedback on the regional characteristic of the water cycle need a detailed exploration in future research. Furthermore, using other accessible gridded climate data to replicate the study is suggested to provide an improved understanding of the uncertainty related to PET variations. It is recommended that local calibration of PET over the Iraqi land is often needed to minimize the uncertainty in estimating PET. Although PET data calculated based on pan evaporation, eddy covariance, and lysimeter are not available in Iraq, it is possible to compute PET for future research using these measurements to compare and support the obtained results and reduce the uncertainty in PET estimation. Moreover, employing multiple criteria for selecting the applied model is also suggested to minimize the uncertainty associated with PET estimation.

The spatial trend analysis carried out in this study can be repeated in other Middle Eastern countries sharing the same climate conditions as Iraq. Also, the applied PET estimation method can be employed in other regions with different climate conditions. It is because the global ERA5-Land dataset provides all the required reanalysis climatic parameters to conduct the analysis. The obtained results can help understand some phenomena, such as the paradox and the complex interaction between PET and the key factors affecting PET changes, which have not been understood clearly in many regions worldwide. Therefore, this can expand the results in other countries in the world.

PET variations might lead to notable changes in the hydrological cycle in the region, particularly in surface runoff and groundwater recharge. It could cause severe implications for water availability, irrigation management, and agricultural production. Also, PET variations had considerable implications for dryness changes in Iraq. Since PET alternation has played a crucial role in dryness changes in a region, the study highlighted the need for a comprehensive understanding of PET variations in Iraq. The obtained findings of the study have suggested that the impacts of PET variations need more attention in future studies of drought in Iraq. Accordingly, the detected increasing trends in PET in most Iraqi lands should be considered in the drought index assessment studies, as it might provide different outcomes owning the significant rising trend in PET in Iraq in recent years. Thus, studying the PET results and data obtained in this study can help to extend the knowledge in evaluating dry conditions at a regional scale and climate change impacts on local hydrology.

5 Conclusions

In the present study, the trend analysis in the PET over Iraq has been conducted based on comprehensive statistical methods at annual and seasonal scales. The following points are the most crucial findings of this study: (1) The PET has increased significantly over the last four decades under a changing climate, except in the east and southeast, which considerably affects the atmospheric evaporative demand and agricultural water requirements. (2) The increasing pattern of trend significance in PET has been confirmed by the results of trend magnitude, especially in the most influence in the southwest region, with Q_i values of Sen's slope ranging from 0.28 to 0.65 mm/decade. (3) Based on trend analysis, summer experienced the most increasing trend magnitude, followed by spring, autumn, and winter. (4) The increasing trend in PET is attributed primarily to the significant increase in AT, as supported by trend analysis of the relatively high Pearson *r* values (0.77 – 0.88) and the contribution rates of 26 – 94%, especially in the central, southern, and northwestern regions. (5) Although the negative contribution of WS and ATP to PET were significant in the southeastern and southwestern parts of Iraq, they were offset by the positive contribution of AT and SR. (6) The spatial analysis indicated that Al-Tharthar and Al-Razzaza Lakes had the highest PET values for all months and seasons, suggesting that atmospheric water vapor loss from those surface water bodies is highly significant.

The present study suggests that it is most likely that crop water demand and irrigation requirements are increased considerably due to increasing atmospheric evaporative loss caused by the detected rising trends in PET. The results also provided a deep insight into the complex interaction between PET and its primary driving climatic parameters in the region and a scientific reference for sustainable agriculture, accurate hydrometeorology, and integrated water resources management in Iraq.

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Author contribution Both authors equally contributed to conceptualizing and designing the study. Alaa Adel Jasim Al-Hasani downloaded data, performed the necessary analysis, and prepared results and the first draft; Shamsuddin Shahid wrote the programming code for data analysis and repeatedly revised the initial draft to generate the final version.

Data availability All the data are available in the public domain at the links provided in the text.

Code availability The codes used for data processing can be provided on request to the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

Conflict of interest The authors declare no competing interests.

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