

Application of Thornthwaite moisture index to some areas in Türkiye

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Abstract: The source of water, the basic need of all living things in nature, is rainfall. When the same amount of rainfall is insufficient or does not fall globally, some regions experience drought problems. In some areas, floods occur due to excessive rainfall. Apart from the normal process of drought and flood, human interventions such as global warming also play an active role in the occurrence of both natural disasters. In order to track drought, several moisture indices have been developed in the literature. Moisture conditions and the extent of a water deficit in a particular area are usually ascertained using moisture indices, characterizing the equilibrium between water inflows and outflows. In this study, Thornthwaite moisture index (TMI) was used to evaluate moisture deficit. The study was conducted in the provinces of Tokat, Kayseri, Ankara, Konya, Karaman, Afyon, Denizli and Burdur. The first effort for this purpose was made according to the Innovative Polygon Trend Analysis (IPTA) of seasonal variation of rainfall and potential evapotranspiration (PET) values. Regular polygons were not obtained at any station in both data sets. Although precipitation data showed a general decreasing trend in all stations during the summer months except June, PET values had the opposite pattern. The monthly TMI index for all stations showed that there was a moisture deficit from April (except for the Afyon station) to October. A striking finding in the annual TMI results was that negative values were detected at all stations. These findings will contribute to relevant decision makers in water-related planning and awareness studies.

Keywords: Innovative polygon trend analysis, Potential evapotranspiration, Rainfall, Thornthwaite moisture index

Türkiye'deki bazı alanlara Thornthwaite nem indeksinin uygulanması

Öz: Doğadaki tüm canlıların temel ihtiyacı olan suyun kaynağı yağıştır. Küresel olarak aynı miktarda yağış yeterli olmadığında veya düşmediğinde bazı bölgelerde kuraklık sorunları yaşanmaktadır. Bazı bölgelerde aşırı yağış nedeniyle seller meydana gelmektedir. Kuraklık ve sel gibi normal süreçlerin dışında, küresel ısınma gibi insan müdahaleleri de her iki doğal afetin meydana gelmesinde etkin rol oynamaktadır. Kuraklığı takip etmek için literatürde çeşitli nem endeksleri geliştirilmiştir. Belirli bir bölgedeki nem koşulları ve su açığının boyutu genellikle su girişleri ve çıkışları arasındaki dengeyi karakterize eden nem endeksleri kullanılarak belirlenmektedir. Bu çalışmada nem açığını değerlendirmek için Thornthwaite nem indeksi (TMI) kullanılmıştır. Çalışma Tokat, Kayseri, Ankara, Konya, Karaman, Afyon, Denizli ve Burdur illerinde yürütülmüştür. Bu amaçla yapılan çalışmada ilk olarak, yağış ve PET değerlerinin aylık değişimi Yenilikçi Poligon Trend Analizi (IPTA)'ne göre yapılmıştır. Her iki veri setinde de hiçbir istasyonda düzenli poligonlar elde edilmemiştir. Yağış verileri yaz aylarında Haziran hariç tüm istasyonlarda genel bir azalan eğilim gösterse de potansiyel evapotranspirasyon (PET) değerleri tam tersi bir desene sahiptir. Tüm istasyonlar için aylık TMI sonuçları Nisan ayından (Afyon istasyonu hariç) Ekim ayına kadar bir nem açığı olduğunu göstermektedir. Yıllık TMI sonuçlarında tüm istasyonlarda negatif değerlerin tespit edilmesi ise dikkat çekici bir bulgudur. Bu bulgular su ile ilgili planlama ve farkındalık çalışmalarında ilgili karar vericilere katkı sağlayacaktır.

Anahtar kelimeler: Potansiyel evapotranspirasyon, Thornthwaite nem indeksi, yağış, Yenilikçi poligon trend analizi

1. Introduction

Global warming, which affects the hydrological cycle, negatively affects human life by increasing the frequency and severity of weather events such as droughts, storms, and floods. These extreme climate events make managing water resources at regional and local scales difficult (Wang and Liu, 2023). However, in recent times, population growth and the resulting increase in water demand, the threat of global warming, and poor management have negatively affected freshwater resources. Water shortages have emerged in many regions around the world (Salehi, 2022). Moreover, increasing pollution in freshwater resources also negatively impacts water availability (Mishra et al. 2021). As a result of global warming, precipitation, one of the essential meteorological elements, may change in quantity and spatial distribution (Boers et al. 2019). On the other hand, this threat affects the agricultural sector and the entire food chain (Ahmad et al. 2022).

Global climate change shows its effects in different parts of the world as different natural disasters. Türkiye has experienced this situation through hail, floods, inundation, frost, forest fires, drought, heavy rainfall, strong wind, lightning, avalanches, snow, and storms (AFAD, 2020). AFAD divides natural disasters into two classes depending on their slow and sudden occurrence. In this sense, drought is defined as a natural disaster that appears slowly but covers large areas with long-term effects. Drought is different from others because it causes serious environmental, economic, and social problems.

Rainfall falls below normal during drought, which damages the ecosystem and water supplies and upsets the hydrological balance (Kapluhan, 2013). A period of unusually dry weather is another definition of drought. These processes result in the development of unfavorable vegetation conditions (Tabari ve Talaee, 2013). The literature drought categorizes as meteorological, agricultural, hydrological, and sociological. Temporal and spatial changes in meteorological factors produce severe fluctuations in agricultural production. Rainfall, temperature, wind, humidity, and the length and intensity of sunshine are some of the variables that impact agriculture. A region must have the moisture and environmental conditions necessary for plant cultivation for plant production to take place there. Various humidity indexes have been developed in the literature. Humidity indexes are also

used to describe vegetation, soil and climate (Mather 1978).

In this research, the Thornthwaite Moisture Index (TMI) was taken into account in evaluating the humidity conditions of the studied locations. McCabe and Wolock (1992) stated that the TMI indicates water supply relative to demand under current climatic conditions. The TMI is a measure for determining periods of water demand, water surplus, and deficit based on the difference between precipitation and evapotranspiration (Guafeng ve ark., 2016). Water deficit corresponds to the situation where precipitation cannot meet the evapotranspiration demand (Cao et al., 2019). This index is widely used in climate change and water resources studies. Abdulla (2008) investigated the magnitude of water deficit in arid areas in Iraq using the TMI. It was stated that the moisture deficit index for the study region varied between -80 and -94 in Baghdad and Basra stations. Jewell and Mitchell (2009) determined the TMI trends in assessing the future state of the climate of Adelaide, Australia. They stated that the climate of Adelaide will become increasingly drier. Guafeng et al. (2016) evaluated drought's temporal and spatial variation in the Hengduan Mountains region of China with the TMI. It was stated that the annual Thornthwaite humidity index in the Hengduan Mountains varied between -97.47 and 67.43, and obvious spatial heterogeneity was observed in different seasons.

The study aimed firstly to determine the seasonal trend of the precipitation and PET values used in calculating the TMI using innovative polygon trend analysis (IPTA). Secondly, it aims to determine the magnitude of moisture deficit at selected stations in the country using the Thornthwaite moisture index and to discuss the effects of current moisture status on crop production and other meteorological factors.

2. Materials and Methods

2.1. Study area

Türkiye has a mountainous topography with seas on three sides. Because of the mountains' orientation and the variations in landforms, different climate types have emerged. Consequently, there is a significant relationship between Türkiye's topography and climate. This has enabled Türkiye to have geographical areas with varying climates and for microclimates to develop within them. Land use in the context of the

country as a whole depends on the terrain structure and climatic characteristics of geographical regions. To put it another way, engaging in forestry in humid areas, animal husbandry in high mountainous and arid regions, and plant production with distinct plant patterns in each area.

In this study, the TMI was applied to evaluate the humidity conditions of eight provinces (Tokat, Kayseri, Ankara, Konya, Karaman, Afyon, Denizli, and Burdur) in Türkiye. For this purpose, precipitation, maximum and minimum temperature, maximum, minimum, and average relative humidity, solar radiation, and wind speed data of meteorological stations located in the mentioned provinces were used as material. The locations of the stations considered in the study are given in Figure 1. The general feature of these stations regarding drought or humidity is that they are in the normal and slightly dry classes according to the Standardized Precipitation Index (SPI) calculated by

the General Directorate of Meteorology for 2024. Based on the provinces where meteorological stations are situated, the most widely grown irrigated agricultural products, their approximate planting and harvesting dates, and the average potential evapotranspiration (PET) values on these dates are displayed in Table 1.

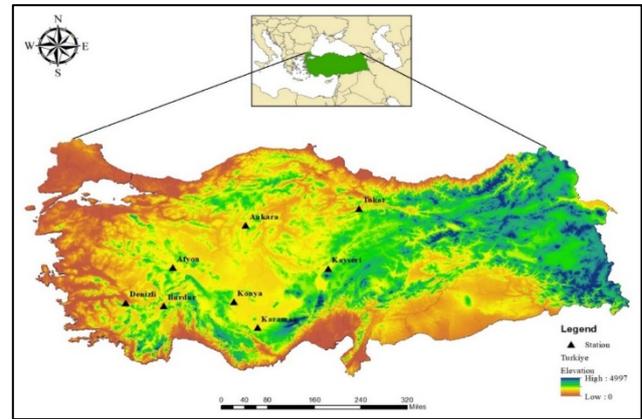


Figure 1. Geographic position of the meteorological stations

Table 1. Period of sowing and harvesting of crops in the studied areas

Station	Period	Crop	Sowing	Vegetation Period (day)	Total PET (mm)
Tokat (SN1)	1984-2022	Maize	May-I	160	579.8
		Sugar Beet	April-I	185	634.3
		Alfalfa	April-I	192	676.7
Kayseri (SN2)	1984-2022	Sugar Beet	April-I	185	613.1
		Alfalfa	April-I	180	597.2
		Potato	April-II	140	495.5
Ankara (SN3)	1984-2022	Onion	April-I	155	573.1
		Maize	May-I	160	603.5
		Sugar Beet	April-I	185	652.0
Konya (SN4)	1984-2022	Maize	May-I	160	600.8
		Sugar Beet	April-I	185	647.6
		Alfalfa	April-I	180	630.9
Karaman (SN5)	1984-2022	Maize	May-I	160	601.4
		Sugar Beet	April-I	185	651.5
		Apple	April-II	190	651.8
Afyon (SN6)	1984-2022	Maize	May-I	160	568.7
		Potato	April-II	140	495.1
		Sugar Beet	April-I	185	614.8
Denizli (SN7)	1984-2022	Maize	March-II	160	635.4
		Grape	March-I	225	856.0
		Cotton	April-II	180	790.8
Burdur (SN8)	1984-2022	Maize	April-III	158	626.3
		Sugar Beet	March-III	185	664.4
		Alfalfa	April-III	180	662.5

Notes: PET: Potential evapotranspiration, March-II: 11-20 March, March-III: 21-31 March, April-I: 1-10 April, April-II: 11-20 April, April-III: 21-30 April, May-I: 1-10 May.

2.2. Innovative Polygonal Trend Analysis (IPTA)

To bring out the type of internal change in monthly rainfall and PET values, this study considered Innovative Polygonal Trend Analysis (IPTA), which is based on the Innovative Trend Analysis (ITA) template developed by Şen et al. (2019). When applying the IPTA approach, the original data is split into two parts as in ITA. This study's IPTA application was based on the internal change in the 12-month seasonal series. The first half (FHS) and the second half (SHS) of the original series were formed based on a matrix, as described by Erdoğan et al. (2025). For IPTA analysis, the average of each half matrix column of rain and PET data was calculated. The mean values for each month's first and second halves were plotted against one another in the Cartesian coordinate system. A straight line was used to join the positioned point for any given month with the one for the following month. The slope and length of the straight line connecting consecutive months were determined according to the coordinates of the points referencing this line. According to Sen et al. (2019), the regular form of IPTA is that roughly half of the points and the lines that connect them are above the 1:1 (45) line, also known as the detrended region, and the remaining ones are below it. The IPTA template of hydro-meteorological variables that occur under unusual physical conditions may take the form of polygons with multiple loops, in contrast to a regular IPTA form with a single-loop polygon. It is possible to make both qualitative and quantitative assessments of the system in which a data set was generated using the IPTA template of that data set. In Şen et al. (2019), a constructed polygon was described in detail.

2.3. Potential Evapotranspiration (PET)

In the study, the potential evapotranspiration required to calculate the TMI was estimated by the Thornthwaite approach. The calculation steps of this method are formulated below.

In the first stage, the mean monthly heat index (i) is calculated using the monthly averaged temperatures (T , °C):

$$i = \left(\frac{T}{5}\right)^{1.514} \quad (1)$$

Based on equation 2, the annual heat index (I) is obtained by summing the heat index (i) for every month. Finally, PET (mm month⁻¹) is calculated based on the following relationship.

$$PET = 16 \left[\frac{10T}{I}\right]^a \frac{N \times d}{12 \times 30} \quad (2)$$

The exponent "a" in the relation is obtained from,

$$a = 675x10^{-9}I^3 - 771x10^{-7}I^2 + 1792x10^{-5}I + 0.492397 \quad (3)$$

Where "N" and "d" correspond to the theoretical sunshine hours and number of days for each month, respectively.

2.4. Thornthwaite moisture index (TMI)

TMI, developed by Thornthwaite and Mather (1955) and modified by Willmott and Feddema (1992), was used to analyze the humidity conditions of the eight provinces selected as study areas. TMI is calculated as in Equation 4.

$$TMI = \begin{cases} P/PET - 1, & P < PET \\ 1 - PET/P, & P > PET \\ 0, & P = PET = 0 \end{cases} \quad (4)$$

Where "P" and "PET" are rainfall and potential evapotranspiration, respectively. Table 2 shows climate classes based on TMI. The TMI is a dimensionless index bounded between "-1" and "1". Grundstein (2009) noted that index values eliminated the decimal number by multiplying the computed TMI values by 100. Positive values indicate a humid climate with excess water, while negative values indicate an arid climate with a water deficit (McCabe and Wolock, 1992). The Thornthwaite method is used to analyze the interaction between energy and surface moisture and to find breaks in climatological and hydrological components that intersect with breaks in vegetation zones (Keim, 2010; Guafeng et al., 2016).

Table 2. Moisture index classes modified by Feddema (1994) (Guafeng et. all, 2016)

Climate	TMI _{min}	TMI _{max}
Arid	-100	-66
Semiarid	-66	-33
Dry subhumid	-33	0
Wet subhumid	0	33
Humid	33	66
Perhumid	66	100

3. Results and Discussion

3.1. Innovative Polygon Trend Analysis Results

In this study, the trend (internal change) of the monthly rainfall and PET data belonging to eight stations was analyzed using the IPTA method. Figure 2 and Figure 3 show the IPTA results based on the arithmetic mean values of rainfall and PET data for each station. The IPTA polygon of all stations for both precipitation and PET data was irregular. This reveals the monthly variability in average values in both data types.

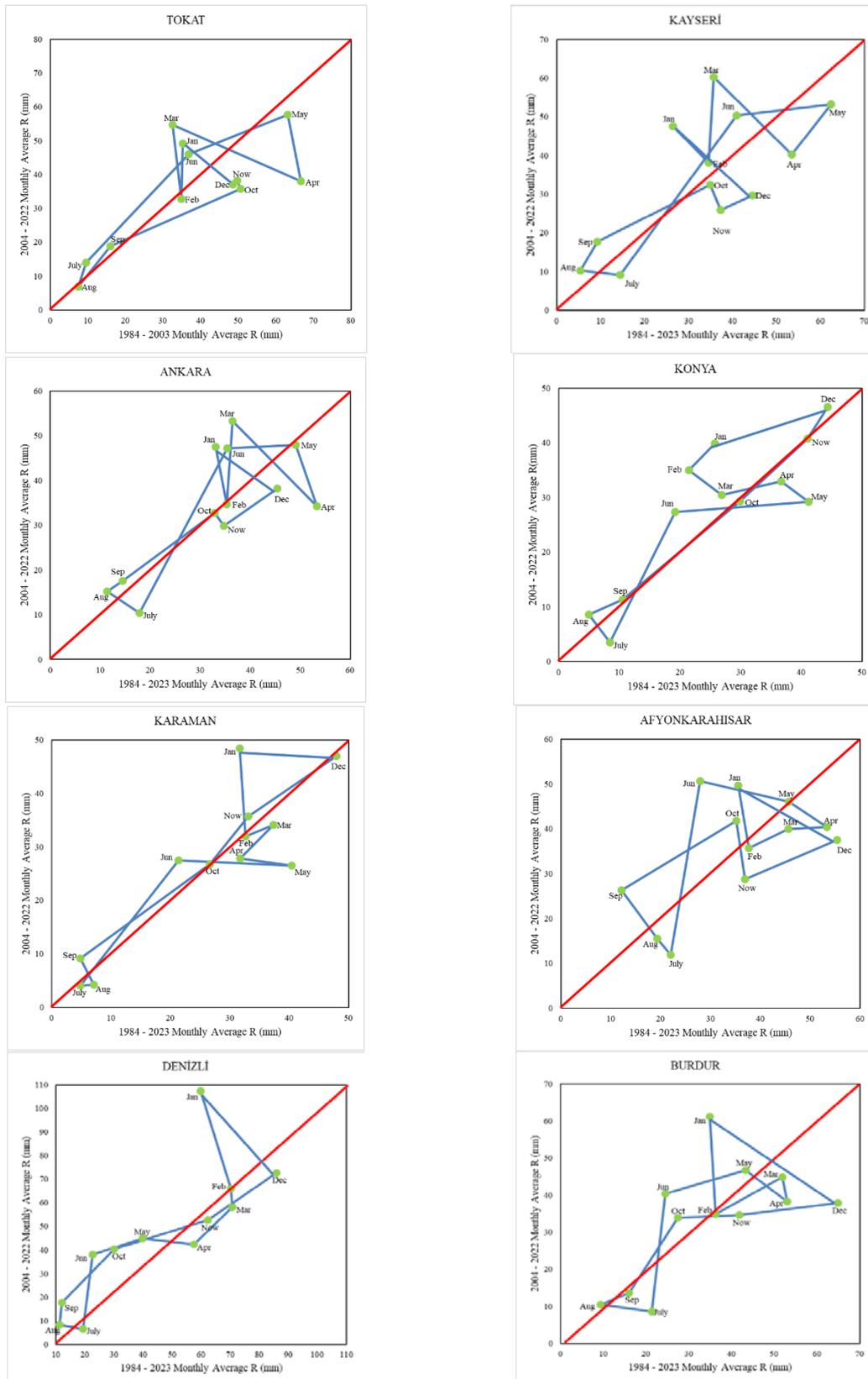


Figure 2. IPTA graph of monthly average precipitation data

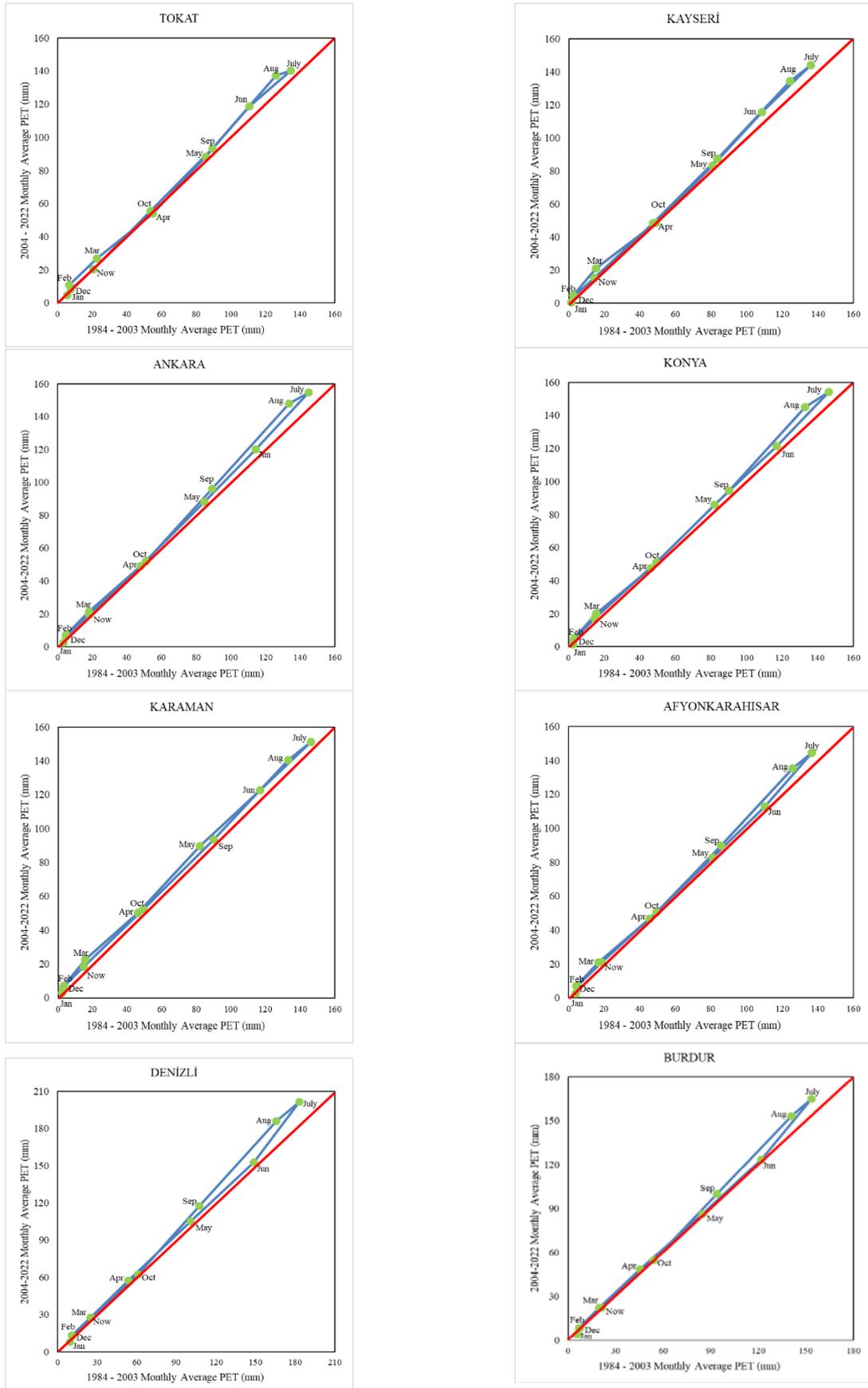


Figure 3. IPTA graph of monthly average PET data

The transition lengths and slopes between trend points by month are given in detail in Table 3 for monthly average rainfall data. When the IPTA graph of the Tokat (SN1) station is examined, it is seen that only August is on the 1:1 line. This indicates that there is no change in August. While the max trend length is between June and July (42.1), the max slope is between January and February, with a value of 43.3. No month was detected on the 1:1 line at Kayseri (SN2) station. The max trend length was determined between June and July, and the max trend slope was found in February and March. An increasing trend was detected in January, February, March, June, August, and September, and a decreasing trend was obtained in the remaining months. When the Ankara (SN3) station data was evaluated, it was determined that there was no trend in February and October; an increasing trend was detected in January,

March, June, August, and September; and a decreasing trend was found in the other months. The max trend length is between June and July, with a value of 40.8, and the max trend slope is found in February and March, with a value of 16.1. When the IPTA graph of the Konya (SN4) station is examined, it is seen that there is no trend in October and November, there is a decreasing trend in April, May, and July, and an increasing trend in other months. The max trend length is between August and September, with a value of 26.4, and the max trend slope is found in June and July, with a value of 2.2. In the context of Karaman station, it is seen that the average values of only February, October, and December are on the 1:1 line. This indicates that there is no change in the months in question. The max trend length and max slope are between June and July, with a value of 28.7 and 1.4, respectively.

Table 3. Trend lengths and slope values of monthly average rainfall data

Station		Month											
		1	2	3	4	5	6	7	8	9	10	11	12
SN1	Trend Length	16.5	22.1	38.1	20.0	28.8	42.1	7.4	14.7	38.6	2.6	1.6	18.1
	Slope	43.3	-9.4	-0.5	-5.6	0.4	1.2	3.4	1.4	0.5	-2.6	0.9	-0.9
	Direction	↗	↘	↗	↘	↘	↗	↗	→	↗	↘	↘	↘
SN2	Trend Length	12.5	22.2	26.8	15.8	21.7	49.1	9.0	8.4	29.7	6.9	8.2	25.5
	Slope	-1.1	20.4	-1.1	1.4	0.1	1.6	-0.1	2.0	0.6	-2.8	0.5	-1.0
	Direction	↗	↗	↗	↘	↘	↗	↘	↗	↗	↘	↘	↘
SN3	Trend Length	13.1	18.7	25.4	14.4	13.7	40.8	8.1	3.9	23.8	3.5	13.6	15.5
	Slope	-5.8	16.1	-1.1	-3.2	0.1	2.1	-0.7	0.8	0.8	-1.6	0.8	-0.8
	Direction	↗	→	↗	↘	↘	↗	↘	↗	↗	→	↘	↘
SN4	Trend Length	6.5	7.0	10.1	5.9	22.1	26.1	6.1	6.3	26.4	16.0	6.6	19.7
	Slope	1.1	-0.8	0.3	-0.8	0.1	2.2	-1.4	0.5	0.9	1.0	1.8	0.4
	Direction	↗	↗	↗	↘	↘	↗	↘	↗	↗	→	→	↗
SN5	Trend Length	16.5	5.1	8.4	8.8	19.1	28.7	2.3	5.4	28.0	11.1	18.6	16.4
	Slope	-16.3	0.5	1.1	-0.2	-0.1	1.4	0.1	-2.2	0.8	1.4	0.8	-0.1
	Direction	↗	→	↘	↘	↘	↗	↘	↘	↗	→	↗	→
SN6	Trend Length	14.2	9.0	7.8	9.4	18.4	39.3	4.5	12.9	27.8	13.2	20.5	23.3
	Slope	-6.4	0.5	0.1	-0.7	-0.3	6.6	-1.4	-1.5	0.7	-7.6	0.5	-0.6
	Direction	↗	↘	↘	↘	→	↗	↘	↘	↗	↗	↘	↘
SN7	Trend Length	42.6	7.8	20.7	17.8	18.5	31.8	8.3	9.5	28.9	34.7	30.9	43.4
	Slope	-3.9	-15.0	1.2	-0.1	0.4	9.6	-0.2	11.1	1.3	0.4	0.8	-1.3
	Direction	↗	→	↘	↘	↗	↗	↘	↗	↗	↗	↘	↘
SN8	Trend Length	26.4	18.6	6.7	13.0	19.8	31.8	12.1	7.3	23.3	14.4	23.3	38.0
	Slope	-19.4	0.6	-6.4	-0.9	0.3	9.8	-0.2	0.5	1.8	0.1	0.1	-0.8
	Direction	↗	→	↘	↘	↗	↗	↘	↗	↘	↗	↘	↘

No trend was detected in May at the Afyon (SN6) station. The maximum trend length and maximum slope are between June and July, with a value of 39.3 and 6.6, respectively. An increasing trend was detected in January, June, August, and September, and a decreasing trend was obtained in other months. Similar results were obtained in the IPTA graph, trend length, and slope values of Denizli (SN7) and Burdur (SN8) stations. It was determined that there was no trend in February at both stations, the maximum trend length was between December and January, and the maximum

slope was between June and July. According to IPTA graphs related to monthly average PET data are examined, it is seen that a similar polygon is formed at all stations (Figure 3). When the trend direction of consecutive months is evaluated, it is determined that there is a trendless and an increasing trend. The average value of January is above the 1:1 line at all stations. The maximum trend length is between August and September, and the maximum slope value is between January and February at all stations (Table 4).

Table 4. Trend lengths and slope values of monthly average PET data

Station		Month											
		1	2	3	4	5	6	7	8	9	10	11	12
SN1	Trend Length	6.2	22.4	42.3	45.9	39.5	32.2	9.1	57.2	52.0	48.2	17.8	4.2
	Slope	4.5	1.0	0.8	1.1	1.2	0.9	0.3	1.2	1.1	1.1	0.9	1.6
	Direction	→	↗	↗	→	↗	↗	↗	↗	↗	↗	→	→
SN2	Trend Length	4.3	20.7	43.4	47.0	42.6	39.7	14.9	62.5	53.2	46.6	16.1	3.8
	Slope	3.9	1.3	0.8	1.1	1.2	1.0	0.8	1.1	1.1	1.0	1.0	2.6
	Direction	→	↗	↗	→	↗	↗	↗	↗	↗	↗	↗	→
SN3	Trend Length	5.0	19.4	40.6	53.8	43.5	46.3	13.3	68.2	58.2	46.1	18.9	4.0
	Slope	4.0	1.1	0.9	1.1	1.1	1.1	0.6	1.2	1.2	1.0	1.0	3.0
	Direction	→	↗	↗	→	↗	↗	↗	↗	↗	→	↗	→
SN4	Trend Length	4.0	19.2	41.0	52.6	49.7	44.1	16.1	66.3	59.4	48.5	17.4	3.0
	Slope	3.7	1.2	0.9	1.1	1.0	1.1	0.7	1.2	1.1	1.0	1.1	3.5
	Direction	→	↗	↗	→	↗	↗	↗	↗	↗	→	↗	→
SN5	Trend Length	4.3	19.7	41.3	53.5	47.8	41.0	16.9	63.6	58.2	48.3	16.6	3.8
	Slope	3.9	1.3	0.9	1.1	0.9	1.0	0.8	1.1	1.0	1.0	1.0	4.5
	Direction	→	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	→
SN6	Trend Length	4.5	18.7	38.6	50.5	42.1	41.1	14.2	60.7	53.7	42.6	19.4	4.5
	Slope	19.4	1.1	0.9	1.0	1.0	1.2	0.8	1.1	1.1	1.0	1.0	5.5
	Direction	→	↗	↗	→	↗	↗	↗	↗	↗	→	↗	↗
SN7	Trend Length	5.3	20.0	41.4	67.2	67.5	59.8	23.4	90.0	71.9	49.8	20.4	5.0
	Slope	3.5	1.0	1.0	1.0	1.0	1.4	0.9	1.2	1.2	1.0	1.1	2.3
	Direction	→	↗	↗	↗	↗	↗	↗	↗	↗	→	↗	↗
SN8	Trend Length	4.9	18.6	36.5	54.8	52.6	52.2	17.3	71.0	60.4	46.1	19.9	4.6
	Slope	3.4	1.1	1.0	1.0	1.0	1.3	0.9	1.1	1.1	1.0	1.0	2.8
	Direction	→	→	→	↗	→	→	↗	↗	↗	→	→	→

The IPTA approach has been used in the literature to examine trends of hydro-meteorological data for numerous basins and regions in Turkey. To give examples of the studies carried out, Susurluk Basin was analyzed by Ceribaşı and Ceyhunlu (2021), Eastern Black Sea Basin by Hırca et al. (2022), Northwestern Part of Turkey by Körük et al. (2023), Elazığ province by Acar (2024), and Van province by Eşit et al. (2024). Many researchers in foreign literature have examined the trend analysis of evapotranspiration data using different methods (Kişi, 2015; Yong et al., 2022; Katipoğlu, 2023; Nunno et al., 2023). When the trend studies conducted for the provinces considered in the study were examined, Köyceğiz and Büyükyıldız (2024) investigated the trend of precipitation data of 11 stations in the Konya Closed Basin using the IPTA method in their study. According to their results, while no significant trend was found in January, August, March, and October at the Konya station, an increasing

trend was observed in June, September, and December. It was stated that there was a decreasing trend in other months. At Karaman station, an increasing trend was observed in January, July, August, September, and December, and a decreasing trend was observed in the remaining months. Eşit (2023) evaluated monthly and annual hydro-meteorological data trends in Ankara province with Mann-Kendall (MK), IPTA, and ITA trend analysis methods. According to the results, the IPTA method successfully captured the precipitation trend. Cengiz (2024) analyzed the precipitation data trends of the stations in the Central Black Sea region with the ITA method. According to the results, an increasing trend was detected in the annual precipitation data at the Tokat station.

3.2. Thornthwaite moisture index (TMI) Results

The monthly estimated potential evapotranspiration (PET) values for each station are shown in Table 3.

Table 3. Monthly Mean Rainfall (mm), Monthly Mean Potential Evapotranspiration calculated by Thornthwaite method (PET) (mm) in the studied areas

Station	R-PET	Months											
		1	2	3	4	5	6	7	8	9	10	11	12
Tokat	R	42.0	33.8	43.4	52.5	60.1	41.6	11.6	7.8	17.1	43.0	45.4	42.6
	PET	5.2	8.7	24.6	54.5	86.8	114.6	137.4	131.5	91.3	54.6	20.6	8.0
Kayseri	R	36.7	36.1	47.1	47.2	57.5	44.8	12.0	7.2	12.9	33.3	33.5	37.0
	PET	1.1	3.7	18.1	48.7	81.9	111.9	139.9	129.4	85.4	47.8	14.9	3.5
Ankara	R	40.1	35.0	44.7	44.0	48.6	41.1	14.2	13.2	16.0	32.8	32.4	41.9
	PET	3.1	6.1	19.8	48.5	86.4	117.1	149.8	140.5	92.5	51.6	19.0	5.6
Konya	R	32.6	28.0	28.6	34.9	35.4	23.1	6.3	6.4	10.9	29.6	40.9	45.4
	PET	1.9	4.3	17.8	46.8	83.9	119.1	150.1	138.8	92.2	50.2	15.9	3.7
Karaman	R	39.8	32.3	35.8	29.9	33.6	24.4	4.5	5.9	6.9	26.7	34.4	47.5
	PET	3.3	5.6	19.8	50.1	87.6	120.2	148.6	136.2	91.8	51.1	17.8	5.9
Afyon	R	42.4	36.7	42.9	47.1	45.9	38.7	17.0	17.5	19.0	38.4	32.9	46.7
	PET	3.3	5.6	18.9	46.1	81.8	111.6	140.5	130.5	87.7	49.8	19.7	5.9
Denizli	R	82.9	68.2	64.6	50.1	42.3	30.2	13.1	9.8	14.7	35.0	57.7	79.5
	PET	8.8	12.0	26.2	55.4	102.9	150.6	192.1	175.5	112.2	61.7	26.5	12.1
Burdur	R	47.7	35.6	48.5	45.8	45.0	32.2	15.2	9.9	14.8	30.6	38.3	51.7
	PET	4.7	7.7	20.9	46.7	85.5	122.6	159.1	146.8	96.8	54.3	21.7	7.6

This table also provides the monthly rainfall (R) amounts required for TMI calculation. There is a significant increase in PET values from April to October compared to the remaining months. This finding was experienced at all stations. In the contexts of monthly total rainfall amounts of the meteorological stations considered in the study, the maximum rainfall amount was experienced in May at the Tokat, Kayseri, and Ankara stations; in December at the Konya, Karaman, Denizli, and Burdur stations; and in April at the Afyon station. These fluctuations in monthly rainfall amounts lead to similar characteristics in TMI. The TMI values are negative in conditions where PET values are higher than rainfall. TMI is an important indicator used to determine water requirements for any area. Especially

irrigated agricultural products such as maize, sugar beet, alfalfa, potatoes, onions, cotton, grapes, and apples, which are grown intensively in the study area and given in Table 1, need irrigation to meet their water needs. The evapotranspiration of these plants is very high during the growing period. Negative TMI indicates that plants would enter moisture stress. When the average monthly rainfall and PET values in Table 3 are examined, it is seen that except for Afyon station, the rainfall amounts of other stations from April to October are less than the PET values. In terms of agricultural production during these periods, it has been revealed that the occurring rainfall amounts could not meet the plants water needs in production. In cases where irrigation is not performed, plants would not be able to complete physiological development.

Table 4. The Monthly Thornthwaite moisture index(TMI) of the studied areas

Station	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
SN1	87.6	74.2	43.3	-3.62	-30.8	-63.7	-91.6	-94.1	-81.3	-21.3	54.7	81.3
SN2	97.1	89.9	61.5	-3.2	-29.7	-60.0	-91.4	-94.4	-84.9	-30.4	55.5	90.6
SN3	92.4	82.7	55.8	-9.1	-43.8	-64.9	-90.5	-90.6	-82.7	-36.3	41.4	86.7
SN4	94.2	84.5	37.8	-25.5	-57.9	-80.6	-95.8	-95.4	-88.2	-41.1	61.0	91.8
SN5	91.7	82.8	44.7	-40.4	-61.6	-79.7	-97.0	-95.7	-92.5	-47.8	48.4	87.7
SN6	92.1	84.6	56.0	2.0	-43.9	-65.3	-87.9	-86.6	-78.3	-22.9	40.2	87.3
SN7	89.4	82.4	59.5	-9.5	-58.9	-80.0	-93.2	-94.4	-86.9	-43.2	54.1	84.8
SN8	90.1	78.3	57.0	-1.9	-47.4	-73.7	-90.5	-93.2	-84.7	-43.7	43.4	85.2

Table 5. The Annual Thornthwaite moisture index(TMI) of the studied areas

Station	Observed Period	P (mm)	PET (mm)	TMI (%)
SN1	1984-2022	440.7	737.7	-40.3
SN2	1984-2022	403.9	686.1	-41.1
SN3	1984-2022	404.1	739.8	-45.4
SN4	1984-2022	317.0	724.9	-56.3
SN5	1984-2022	319.9	737.9	-56.7
SN6	1984-2022	423.3	701.5	-39.7
SN7	1984-2022	548.5	935.9	-41.4
SN8	1984-2022	415.4	774.4	-46.4

Using the R and PET values in Table 3, moisture index values (TMI) were calculated monthly and annually according to Equation 3 and are given in Tables 4 and 5, respectively. Each calculated TMI value was assigned a climate class according to Table 2. TMI results showed that five months (January, February, March, November,

and December) of all stations were in the humid climate class. Still, in addition to these months, April was also in the humid class at Afyon station. When evaluated in terms of monthly TMI results, the most drought month in Tokat, Kayseri, Ankara, Denizli, and Burdur stations was August, for which the TMI value for the stations in

question varied between -90.6 and -94.4 (Table 4). For the remaining three stations (Konya, Karaman, and Afyon), the driest month was July, and the TMI values of the three stations in this month were calculated between -87.9 and -97.0 (Table 4). Table 5 shows that annual TMI findings revealed that all stations were in the semiarid climate class. In terms of annual TMI results, the most severe drought was obtained at Karaman station with a TMI value of -56.7.

4. Conclusion

In this study, Thornthwaite moisture index (TMI), or in other words the moisture deficit index, was calculated by using temperature and precipitation data from eight stations (Tokat, Kayseri, Ankara, Konya, Karaman, Afyon, Denizli, and Burdur) located in the central Black Sea, Central Anatolia, Mediterranean, and Aegean regions of Türkiye. This index is essential for understanding various biophysical processes including soil surface wetness, surface energy balance, soil moisture, hydrology, and various biological processes.

In the first stage, seasonal variability of the rainfall and PET data were investigated. Based on the results, regular polygons were not formed in both data sets at all stations. This situation indicates that the arithmetic means of the data are not constant. It was determined that rainfall data generally showed a decreasing trend in the summer months, except June, at all stations, and PET values showed an increasing trend in the mentioned months.

According to the monthly TMI index results, there was a moisture deficit from April (except Afyon station) to October, the TMI index values were negative. On the other hand, the months in which the highest moisture deficit was detected were July and August. These results emphasize that irrigation is necessary for plant production during the mentioned period. Otherwise, it will be difficult for cultivated plants to perform their physiological activities. Another remarkable finding was detected in the annual TMI results. Annual TMI index values were negative at all stations. TMI values calculated both monthly and annually should ensure that decision-makers pay attention to the necessary planning and awareness studies regarding the effective use of water resources in the areas studied, in terms of the reliability of agricultural production. Nowadays, where the effects of climate change are apparent, monitoring the TMI change and determining the plant pattern to be grown in these regions are extremely

important for the sustainable and effective use of water resources. In addition, pressurized irrigation methods instead of surface irrigation and the preference for drought-resistant varieties will make the cultivation of these crops more successful in periods when the water deficit is high. In the study area, practical application of irrigation methods such as sprinkler (alfalfa, sugar beet) and drip irrigation (corn, potato, onion, apple, grape, and cotton), considering the specific needs of each plant type, will maximize the total yield potential. Water distribution programs should be prepared and implemented following TMI index. In basins where agricultural groundwater is deemed insufficient and the Ministry of Agriculture and Forestry restricts water, no support payment will be made for maize for grain, except for areas irrigated with drip irrigation, with the planned support model for 2025-2027. In the regions of Konya, Karaman, and Ankara, which are subject to water restrictions, water restriction support will be paid in addition to regular support when plants that do not need water or have minimal water requirements during the irrigation season are planted. In addition, pivot and subsurface drip irrigation applications that will increase irrigation efficiency should be widespread.

Conflict of interest

The authors declare no conflicts of interest.

Authorship contribution statement

All authors contributed to the concept and design of the study. Müberra Erdoğan Karaağaçlı and Mehmet Murat Cömert carried out data collection, data curation, and data analysis. Kadri Yürekli applied the methodology. All authors read and accepted the final version of the manuscript.

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