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RESEARCH

A comprehensive analysis and comparison of SPI and SPEI for spatiotemporal drought evaluation

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Abstract Assessing drought is crucial for effective water resources management and the development of mitigation strategies. Drought indices serve as indispensable tools in this evaluation process, and choosing an appropriate index is vital for accurate drought assessment. The characteristics and classification of drought depend entirely on the chosen index. Based on the existing literature, the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) are the most commonly and widely used indices, and there is a significant need for a comprehensive comparison between SPI and SPEI to understand their differences and implications for drought assessment. This research aims to compare SPI and SPEI based on drought indices, characteristics, and classifications using the innovative drought classification matrix (IDCM) for spatiotemporal drought evaluation, and the comparison process is done for events and monthly scales. Also, it aims to investigate the comparison between SPEI obtained from in situ meteorological stations and from the SPEI database. The application and the comparison are presented for Istanbul city between 1951 and 2020. The results show similar variations and high correlation (more than 0.65) between SPI and SPEI. For drought characteristics, there is no consistent relationship between SPI and SPEI at the drought event scale. The outcomes revealed that approximately 60% of the months exhibit consistent drought classifications between the two indices. Finally, it shows a significant difference between SPEI based on in situ meteorological stations and satellite data. The comparison between SPI and SPEI based on different aspects is necessary and essential for drought studies and water resources management.

Keywords Spatiotemporal drought · Drought characteristics · Drought classification · Comparison · SPI · SPEI

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Introduction

Droughts are identified as environmental catastrophes and are noticed by hydrologists, environmentalists, metrologists, and agriculturists (Sai et al., 2021; Yanjun et al., 2012). Droughts occur in any climatic area, in low- and high-precipitation regions, and concern a reduction in the amount of precipitation over a specific duration (Ekmekcioğlu et al., 2021; Tigkas et al., 2019). The occurrence of droughts is based on numerous hydro-meteorological variables such as temperatures, low relative humidity, and precipitation, which is one of the most critical variables characterized based on the precipitation intensity and duration as well as the beginning and termination of the rain. According to the recent UN World Water Development Report (UN-Water 2020), approximately 4 billion people face water deficiency for at least 1 month yearly. The destructive impacts of drought lead to global economic losses exceeding 6 billion dollars (Ben Othman & Abida, 2022; Wilhite, 2016).

According to Wilhite (2016) and Dai et al. (2018), drought is classified into four distinct types: meteorological, agricultural, hydrological, and socioeconomic droughts. Because of population growth and the expansion of the industrial, energy, and agricultural sectors, water demand has significantly increased; consequently, water scarcity has occurred nearly every year in several parts worldwide (Dogan et al., 2012; Riebsame et al., 1991). Regarding the State Meteorological Service (MGM, 2022), the precipitation in Istanbul decreases yearly. In addition to the reduced precipitation, excessive water resource consumption and increased drought have inverse impacts on Istanbul's climate and water resources. Also, climate change and pollution of water supplies have a dominant contribution to water scarcity (Makineci, 2022; Şişman, 2019). They are the main reason for reduced water supply, crop failure, declining water quality, and decreased power energy, as well as affecting social and economic activities (Gond et al., 2023; Şen, 2018; Nalbantis & Tsakiris, 2009; Tsakiris & Loucks, 2023). According to the Istanbul Water and Sewage Administration (ISKI, 2023), the occupancy rate in Istanbul's dams was 19% in October 2023, the minimum rate in the last 15 years.

Various standardized drought monitoring indices have been proposed in the literature to evaluate drought quantitatively and qualitatively worldwide. Each drought index depends on one or multiple variables representing a particular drought. For example, the Standardized Precipitation Index (SPI) (McKee et al., 1993) is based on precipitation, and the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) is based on the difference between precipitation and potential evapotranspiration. The standardization also has the advantage of transforming the drought index into a non-dimensional index for comparison goals. Therefore, the drought indices are the main and first step for drought assessment and deriving drought characteristics. The month-based timescale is considered more suitable for drought analysis related to water supply, groundwater, and agriculture (Panu & Sharma, 2002).

As mentioned above, several drought indices can be used, and due to this variety, selecting the most appropriate index has been the existing subjects and trends in the most recent research (Şişman, 2020; Wable et al., 2018). Each index has specific inputs and assumptions, which are used without considering the differences and assumptions between them. Also, data availability and spatial distribution of these data are significant factors in selecting an appropriate drought index for drought evaluation. For example, in instances where only precipitation data is available, the analysis will be limited to calculating SPI, and the researchers use one data source to study the drought without considering other sources. Furthermore, the drought index selection process also depends on the purpose of the drought analysis, which is used as an indicator for risk assessment and hydrological design purposes (Abu Arra & Şişman, 2023; Abu Arra et al., 2024a). Regarding data sources, meteorological data and some drought indices are obtained from in situ meteorological stations, satellites, and global models such as SPEI (SPEIbase) (https://spei.csic.es/database.html), which gives a large scale, such as 0.5° spatial resolution. In other words, a single or small number of grid cells are used for some cities and regions. After a thorough review of the existing literature for the points mentioned above, the main questions of this research are as follows: What is the difference between the mostly used drought indices? Which index should be used for each purpose? Which data source must be used, particularly for regions facing data availability challenges and what is the difference between these sources? In this situation, which is better, and what is the difference between using a single or limited number of grid cells and using a limited number of in situ meteorological stations?

Understanding drought comprehensively is paramount for effective mitigation and management strategies. The selection of appropriate drought indices is crucial, and the comparison between commonly used indices like the SPI and the SPEI is pivotal for an accurate evaluation. Furthermore, choosing a data source adds another layer of complexity, as different sources may yield distinct results. Addressing the spatial aspect of drought evaluation introduces whether a single or limited number of grids suffice or if a more localized approach using in situ meteorological stations is more accurate. These critical questions remain largely unexplored in the existing literature, creating a significant gap in our understanding of drought dynamics that necessitates urgent attention and research efforts. Filling this void will contribute to scientific knowledge and enhance our ability to develop targeted and effective drought management strategies. The main objectives of the study are (1) to determine the similarities and differences exhaustively between the most used drought indices (SPI and SPEI) using new framework based on drought index, characteristics, and classification for both event and month scales; (2) to investigate the comparison between SPEI obtained from in situ meteorological stations and from SPEI database with regard to drought index and drought classification using the innovative drought classification matrix (IDCM), proposed by Abu Arra and Şişman (2024), which is not explored in the literature; (3) and should satellite and global models or weather stations be used in cases of low data availability? To comprehensively address these questions and gaps, Istanbul city is selected as a case study, utilizing data from 1951 to 2020.

Study area and data collection

The application presented monthly precipitation records from Istanbul's metropolitan city in northwest Türkiye. The city is located between the Black Sea and the Marmara Sea. Also, the Bosporus is located in the middle of Istanbul, separating it into two continents, Asia and Europe. The latitude and longitude of Istanbul are 41.00527° and 28.97696° (as shown in Fig. 1). According to the statistics of TUIK (2022), Istanbul has a population of approximately 15.96

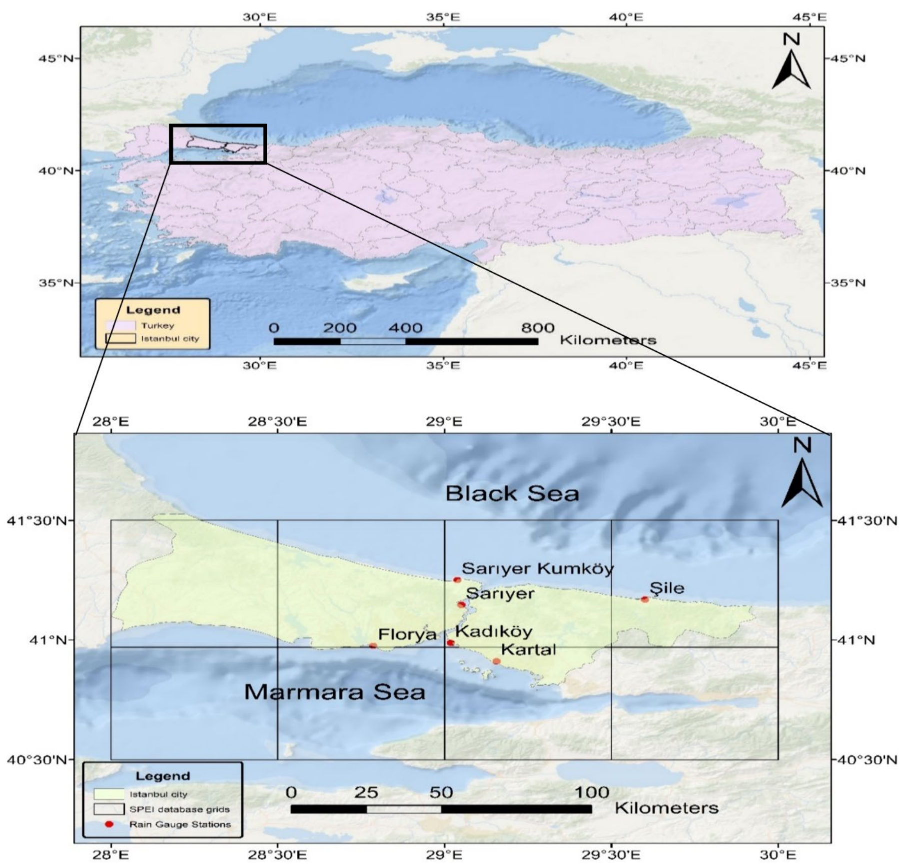


Fig. 1 Location of Istanbul city, the meteorological stations, and the grid data obtained from the SPEI database

million people and is recognized as the most populous city in Türkiye. It is also a large and speedily developing and expanding city. The total area of Istanbul is 5461 km^2 (HGM, 2014).

The climate of Istanbul is described as mild; the summer is hot and humid with very little rain, and the winter is cold, wet, rainy, and with some snow. Spring and autumn are mild. The city's average annual temperature is 13. 7 °C, as reported by MGM in 2010. Precipitation occurs almost every month in Istanbul, with an annual total of 845 mm (MGM, 2022). The distribution of precipitation over seasons is as follows: 38% in winter, 18% in spring, 13% in summer, and 31% in autumn. As with practically every part of the world, the effect of climate change in Istanbul is increasingly becoming more severe, including floods and droughts (Güçlü et al., 2018; Toros et al., 2017).

According to the ISKI (2023) report, Istanbul is in danger of extraordinary drought, and the occupancy rate of the dams supplying water to Istanbul has decreased to 19%, the lowest percentage in the previous 15 years. Surface water and dams are the main water resources in Istanbul, and reducing by 1% affects millions of people, agriculture, and many sectors. Because of the importance of Istanbul city, a huge need exists to analyze and assess the drought condition. For Istanbul, satellite and remote sensing data are characterized by a specific number of gridded points, constraining the comprehensive understanding of its complex drought situation. Figure 1 shows the distribution of six meteorological stations with the grided points obtained from the SPEIbase. Subsequently, using six in situ meteorological stations well distributed near the city's coastal locations can be a more reasonable choice. The average monthly temperature and precipitation data of six meteorological stations were obtained between 1951 and 2020 from the Turkish State Meteorological Service (TSMS); the data is available only in six stations for a long period. Firstly, all obtained data were analyzed and checked for continuity and consistency, and the missing values were corrected with average values from adjoining meteorological stations. The statistical calculations for both temperature and precipitation data of six stations are summarized in Table 1.

Methodology

Standardized Precipitation Index (SPI)

The SPI method was utilized to calculate the meteorological drought in Istanbul at several timescales (3, 6, 9, 12, and 24 months) depending only on the monthly precipitation data (70 years). The original monthly precipitation data is fitted to the appropriate probability density function (PDF). According to Wang et al. (2019), the gamma PDF is the best distribution for calculating SPI in most cases. The goodness-of-fit tests are checked for precipitation by chi-square and Kolmogorov-Simirnov tests (Stephens, 1970). After that, theoretical probabilities are probabilistically standardized into standard normal PDF. The probabilistic standardization procedure differs from the statistical standardization procedure, which transforms the PDF into a normal PDF utilizing cumulative probabilities instead of shifting the mean (Şen & Almazroui, 2021; Şen & Şişman, 2023). More details about SPI can be found in McKee et al. (1993).

Table 1 Geographical and climatic information and basic statistics of the observed monthly precipitation and temperature data

Station's name	Station ID	Latitude (N)	Longitude (E)	Mean precipitation (P) — mm	Standard deviation (mm)	Mean temperature (T) —°C	Standard deviation (°C)
Sarıyer Kümköy	17,059	41.25	29.03	66.12	54.14	14.12	6.52
Sarıyer	17,061	41.14	29.05	68.39	53.25	14.01	6.51
Kadıköy Rıhtım	17,062	40.98	29.01	55.74	45.5	14.64	6.67
Şile	17,610	41.16	29.60	67.59	56.57	13.81	6.39
Florya	17,636	40.97	28.78	53.78	44.08	14.42	6.74
Kartal*	17,638/17064	40.91	29.15	53.48	43.44	15.23	6.73

*Kartal meteorological station was a manual station until 2003 with code 17,638, then an automatic station with code 17,064 was installed at a nearby location

The gamma distribution's probability density function is defined as:

$$g(x) = \frac{1}{\beta^{\alpha} T(\alpha)} X^{\alpha-1} e^{\frac{-x}{\beta}}, \text{for} x > 0 \quad (1)$$

where α and β are the shape and scale parameters, respectively, and x is the precipitation. $T(\alpha)$ is the gamma function. The shape and scale parameters can be calculated using the approximation of Thom:

$$\alpha = \frac{1}{4A}(1 + \sqrt{1 + \frac{4A}{3}}) \quad (2)$$

and

$$\beta = \frac{\overline{X}}{\alpha} \quad (3)$$

with

$$A = \ln\left(\overline{X}\right) - \frac{\sum \ln(X)}{n} \quad (4)$$

where $\overline{X}$ is the average precipitation, n is the number of data, and X is the precipitation at a current period.

Standardized Precipitation Evapotranspiration Index (SPEI)

The SPEI method was developed by Vicente-Serrano et al. (2010). For the calculation of SPEI, potential evapotranspiration was calculated using the Thornthwaite method (Thornthwaite, 1948), which is only based on monthly temperature data. The main parameter in SPEI calculation is the difference between precipitation and evapotranspiration values called water balance. The calculated water balance is also fitted to the most suitable PDF, and in the research, it is a three-parameter log-logistic function. In most cases, log-logistic is the best PDF for estimating SPEI (Wang et al., 2019). Moreover, the goodness-of-fit has been checked for water balance data by chi-square and Kolmogorov-Simirnov tests (Stephens, 1970). Subsequently, the obtained probabilities are transformed into a sequence of a standard normal PDF using the following classical approximation of Abramowitz et al. (1965). More details about SPEI can be found in Vicente-Serrano et al. (2010).

Drought identification and characteristics

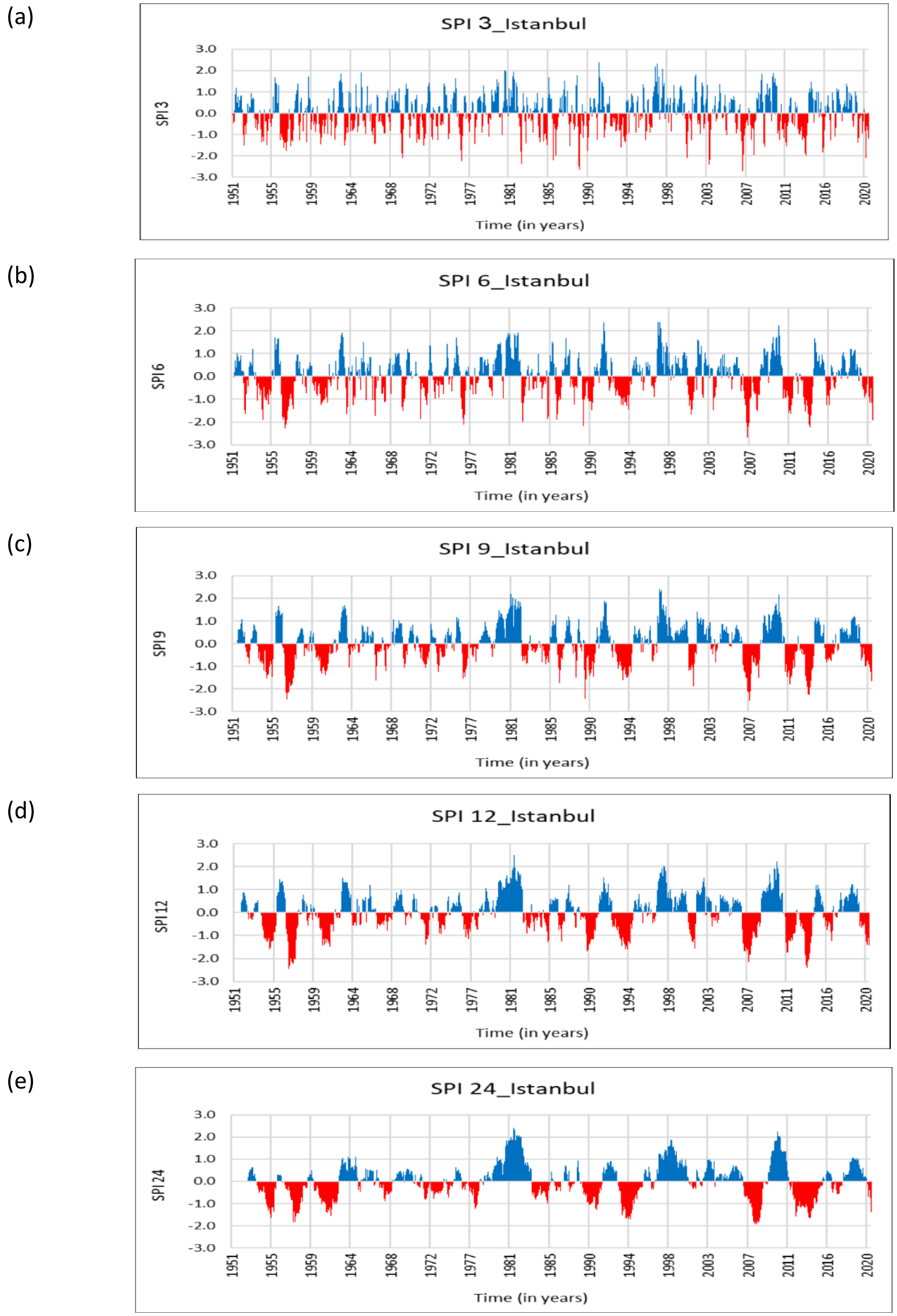
This study calculates SPI and SPEI values at several timescales (3, 6, 9, 12, and 24 months). For example, SPI3 measures the drought index based on the precipitation record over a 3-month period. Furthermore, the determination of the drought is based on the classification of SPI and SPEI values, which are the standard normal PDF. McKee et al. (1993) classified the drought into seven categories, as shown in Table 2. The negative values indicate drought events, and the positive values indicate wet events. Drought events and characteristics differ based on the drought definition (Abu Arra & Şişman, 2023). For example, according to McKee et al. (1993), drought events begin when the drought index value in a specific month falls under − 1 and ends when the drought index returns to a positive value. Drought duration is the number of months between starting and ending point. The severity (S) can be defined as the integral area between the SPI/SPEI line and the X-axis (when the SPI/SPEI value is zero) within the drought duration. Finally, the drought intensity (I) can be calculated by dividing the severity by drought duration.

Pearson's correlation analysis

Pearson's correlation coefficient (R) is a widespread technique for measuring and assessing the linear correlation and consistency of the drought indices (SPI/SPEI). R was calculated between SPI and SPEI for each month during 70 years and summarized as a heatmap.

Table 2 Drought classification according to SPI and SPEI (McKee et al., 1993)

SPI/SPEI values (Drought Index_DI)	Drought classification	Probability (%)
$2.00 \leq DI$	Extreme wet (EW)	2.3%
$1.50 \leq DI < 1.99$	Severe wet (SW)	4.4%
$1.00 \leq DI < 1.50$	Moderate wet (MW)	9.2%
$-0.99 \leq DI < 1.00$	Normal (N)	68.2%
$-1.50 \leq DI < -1.00$	Moderate drought (MD)	9.2%
$-2.00 \leq DI < -1.50$	Severe drought (SD)	4.4%
$-2.00 > DI$	Extreme drought (ED)	2.3%


(a)
SPI 3_Istanbul
SPI 3
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
1951 1955 1959 1964 1968 1972 1977 1981 1985 1990 1994 1998 2003 2007 2011 2016 2020
Time (in years)
(b)
SPI 6_Istanbul
SPI 6
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
1951 1955 1959 1964 1968 1972 1977 1981 1985 1990 1994 1998 2003 2007 2011 2016 2020
Time (in years)
(c)
SPI 9_Istanbul
SPI 9
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
1951 1955 1959 1964 1968 1972 1977 1981 1985 1990 1994 1998 2003 2007 2011 2016 2020
Time (in years)
(d)
SPI 12_Istanbul
SPI 12
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
1951 1955 1959 1964 1968 1972 1977 1981 1985 1990 1994 1998 2003 2007 2011 2016 2020
Time (in years)
(e)
SPI 24_Istanbul
SPI 24
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
1951 1955 1959 1964 1968 1972 1977 1981 1985 1990 1994 1998 2003 2007 2011 2016 2020
Time (in years)

◂**Fig. 2** Temporal variation of SPI at (**a**) 3-month, (**b**) 6-month, (**c**) 9-month, (**d**) 12-month, and (**e**) 24-month timescales between 1951 and 2020 in Istanbul

$$R = \frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}} \tag{5}$$

where X_i and Y_i are the SPI and SPEI values. $\overline{X}$ and $\overline{Y}$ are the means of SPI and SPEI, respectively.

Innovative drought classification drought matrix

This matrix was proposed by Abu Arra and Şişman (2024) to investigate the differences between drought indices, different locations, and different time periods based on drought classification. The comparison process is done month by month, and the most important result of this matrix is the summation of the months located within the same drought classification. This research uses this matrix to compare SPI and SPEI, as well as SPEI values obtained from in situ meteorological stations and global products.

Differences between SPEI values obtained from in situ meteorological stations and global products

Two choices are available for SPI and SPEI calculations. The first choice is to use the available six meteorological stations, and the second is to use the global products, such as SPEIbase. This research used the SPEIbase for SPEI values at different timescales as well as six meteorological stations to find the difference between them, according to drought index and drought classification. Any change in DI is considered and is shown in detailed figures in the "Results" section.

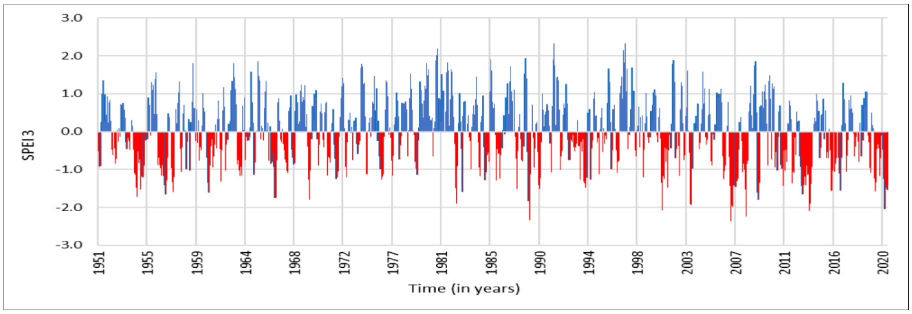
Results

To find a representative value of each timescale drought index for the whole of Istanbul, the arithmetic mean (AM), median (M), and weighted arithmetic mean (WAM) of SPEI and SPI values were calculated for all stations. Generally, the arithmetic mean is used as a representative value for temporal analysis and assessment in the literature (Serkendiz & Tatli, 2023). This research answers the question about which value can be used as a representative value and whether there is any difference between them. The results show that all stations' correlation coefficient is more than 0.90. For example, for SPI3, the correlation coefficient between the arithmetic mean and the median was 0.98. Increasing the timescale leads to a lower correlation between statistics. For SPEI24, the correlation between M and WAM is 0.906, which is acceptable but lower than other correlation values. The correlation coefficients generally indicate a strong positive correlation between AM, M, and WAM. Subsequently, any statistical value such as AM, M, or WAM can be used as a representative drought index for all of Istanbul. In this research, AM has been used as a representative value for temporal evaluation and assessment.

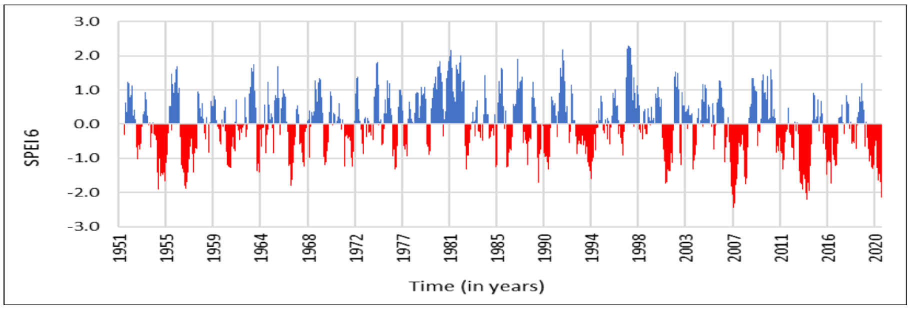
Temporal assessment of SPI and SPEI at several timescales using in situ meteorological stations

The SPI and SPEI were calculated at 3-, 6-, 9-, 12-, and 24-month timescales between 1951 and 2020 (70 years) in Istanbul city. The first finding was that the dry and wet events based on several timescales did not happen with the same months, severity (*S*), and intensity (*I*). This indicated the importance of the selected timescale, which directly affected the results. So, depending on the purposes of drought evaluation, the timescale must be considered carefully. Also, a considerable increase in drought events, duration, and severity has been identified after 1999 for all timescales, while from 1951 to 1999, normal drought conditions were frequent. At a short timescale, such as 3 months, the SPI and SPEI have shown higher frequent drying events (Figs. 2a and 3a). On the other hand, the frequency and variation between dry and wet events decreased at longer timescales, such as 6, 9, and 12 months. Also, it was noticed that both drought duration and severity were higher (Figs. 2b–d and 3b–d), indicating the annual and seasonal variation of water balance regarding the hydrological drought. At a longer timescale (24 months), the frequency decreased with a significant increase in drought duration (Figs. 2e and 3e), reaching up to 79 months (Fig. 3e), which is more than the expected duration based on previous timescales, and the magnitude increased (Table 3).z

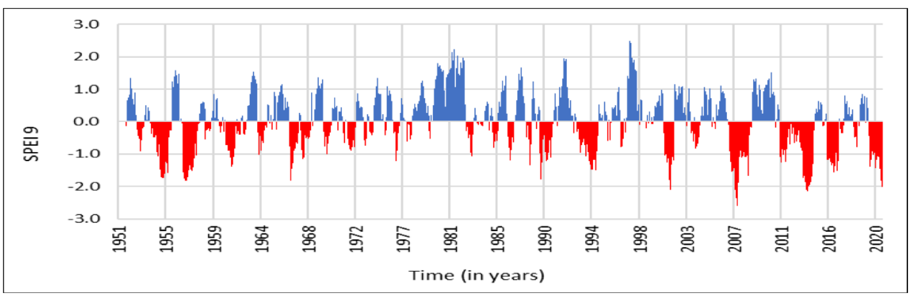
(a)


SPEI 3
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
1951 1955 1959 1964 1968 1972 1977 1981 1985 1990 1994 1998 2003 2007 2011 2016 2020
Time (in years)

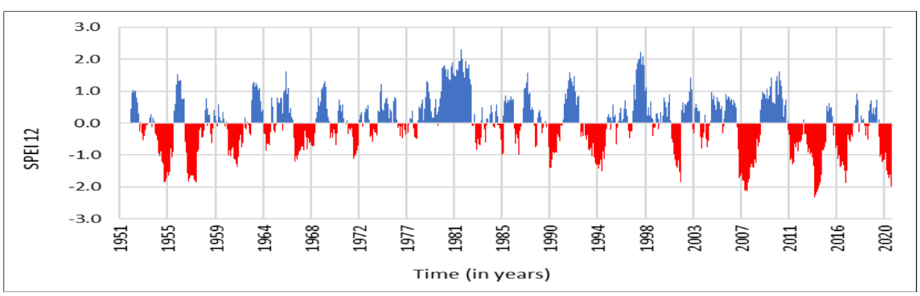
(b)


SPEI 6
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
1951 1955 1959 1964 1968 1972 1977 1981 1985 1990 1994 1998 2003 2007 2011 2016 2020
Time (in years)

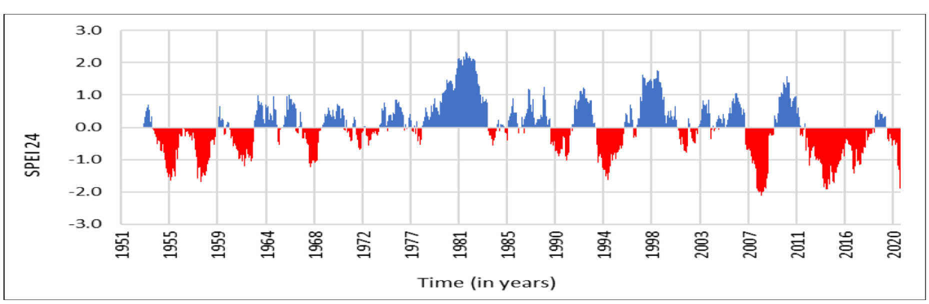
(c)


SPEI 9
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
1951 1955 1959 1964 1968 1972 1977 1981 1985 1990 1994 1998 2003 2007 2011 2016 2020
Time (in years)

(d)


SPEI 12
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
1951 1955 1959 1964 1968 1972 1977 1981 1985 1990 1994 1998 2003 2007 2011 2016 2020
Time (in years)

(e)


SPEI 24
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
1951 1955 1959 1964 1968 1972 1977 1981 1985 1990 1994 1998 2003 2007 2011 2016 2020
Time (in years)

◂**Fig. 3** Temporal variation of SPEI at (**a**) 3-month, (**b**) 6-month, (**c**) 9-month, (**d**) 12-month, and (**e**) 24-month timescales between 1951 and 2020 in Istanbul

Figure 2 and Fig. 3 show the differences between SPI and SPEI at several timescales. Drought duration, severity, and intensity were not exactly similar during the same period. Furthermore, drought characteristics depending on the SPEI have more severity (maximum drought severity was −2.6 in August 2007), and duration has increased significantly (maximum duration was 79 months) (Table 3). The SPI relies only on precipitation data to calculate the drought index and events, making it a straightforward and simple measure. On the other hand, the SPEI incorporates both precipitation and evapotranspiration, providing a more comprehensive view of drought conditions by considering the water balance. The inclusion of evapotranspiration makes SPEI more sensitive to temperature and soil moisture variations using the Thornwaite method, which can intensify drought severity and duration under warming climate conditions. In addition, using different PDFs for SPI and SPEI calculations contributes to the observed differences. The SPEI's ability to measure both the impacts of precipitation decline and increased evapotranspiration often leads to longer duration and more severe drought events compared to SPI, which may only reflect precipitation deficit. These methodological differences indicate why SPEI may show and lead to longer and more intense drought events, as proved in this research.

Spatiotemporal assessment of drought characteristics

Drought characteristics were calculated based on SPI theory (McKee et al., 1993) at the threshold of −1 until 0 for several timescales. Spatial distribution for both intensity and duration has been calculated using the inverse distance weighted (IDW) method. The IDW method is highly confident in drought analysis (Abu Arra et al., 2023). The spatial distribution using IDW was analyzed by ArcMAP. Figure 4 shows the spatial distribution of drought duration (D) for SPI and SPEI in the study area. Drought events based on SPEI have longer durations than SPI for 3- and 6-month timescales. However, for longer timescales (9, 12, and 24 months), the SPI-based drought events have a longer duration than SPEI. However, spatial distribution for SPEI-based drought events has more dry areas (see Fig. 4). Also, the spatial distribution of drought duration indicates that the eastern and center parts of Istanbul observed drought events have a longer duration for SPEI. In contrast, the SPI-based drought events have a higher duration in the eastern parts. In general, the spatial distribution of drought duration in the western part of Istanbul is relatively shorter for both SPI- and SPEI-based drought events.

The spatial distribution of drought intensity (I) for both SPI- and SPEI-based drought events is illustrated in Fig. 5. The change in color from red (higher drought intensity) to blue (lower drought intensity) reflects the change in drought intensity over the study area. Also, intensities have been a little different at all timescales. SPI-based drought intensities were generally slightly higher at the same timescales than SPEI. Also, the spatial distribution of high drought-intensity parts differed for SPI- and SPEI-based drought events. For example, for SPI9, the high drought-intensity area was in the southern part of Istanbul, while the high drought-intensity area for SPEI9 was in both the southern and northern parts of Istanbul. In conclusion, drought characteristics based on SPEI and SPI changed slightly and extremely spatially and temporally.

Table 3 shows several statistical parameters (average, median, maximum, minimum, and standard deviation) regarding drought characteristics such as duration and intensity, relying on SPI (McKee et al., 1993) theory for both SPI and SPEI_based drought events. The monthly median duration and intensity value for SPI- and SPEI-based drought events were approximately similar for all stations. There was no significant difference between them. Then, the average values as representative values were used. According to Table 3, it can be noticed that there was a significant difference between SPI and SPEI statistics for all stations and characteristics at all timescales. For the Sarıyer Kumköy station, the drought average duration and intensity at 3-, 6-, and 24-month timescales were remarkably similar for SPI- and SPEI-based drought events, with a minimal difference. However, according to the SPEI-based drought events, the average duration and intensity at 9- and 12-month timescales were higher than those obtained based on SPI. Also, for Florya, the drought characteristics for both SPI- and SPEI-based drought events were approximately the

Table 3 Statistical parameters of duration and intensity for all SPI- and SPEI-based drought events for all meteorological stations in Istanbul from 1951 to 2020

	Average		Median		Max		Min		SD	
	D	*I* (−)	*D*	*I* (−)	*D*	*I* (−)	*D*	*I* (−)	*D*	*I* (−)
SPI3										
1*	4.17	1.10	3	1.10	21	2.19	1	0.63	3.31	0.33
2	4.19	1.07	3	1.04	19	2.07	1	0.37	3.55	0.35
3	4.44	1.14	3	1.11	21	1.99	1	0.62	4.10	0.29
4	4.70	1.09	3.5	1.05	21	2.33	1	0.47	3.73	0.41
5	4.19	1.12	3	1.09	17	1.89	1	0.63	3.09	0.33
6	3.96	1.18	3	1.17	15	2.06	1	0.49	3.14	0.34
SPI6										
1	7.44	1.01	6	0.97	22	1.86	1	0.43	5.56	0.33
2	8.79	1.03	7	0.97	21	2.15	2	0.56	5.35	0.37
3	7.20	1.11	4.5	1.18	37	2.21	1	0.46	7.53	0.38
4	8.69	1.04	7	0.95	23	2.30	2	0.51	5.14	0.43
5	7.53	1.03	6	1.01	26	1.68	1	0.50	5.87	0.29
6	7.10	1.08	6	1.08	39	1.80	1	0.66	7.61	0.32
SPI9										
1	9.65	1.03	9	0.97	20	1.79	2	0.59	4.99	0.34
2	12.64	0.97	9	0.87	50	1.79	3	0.50	9.89	0.33
3	11.94	1.04	11	1.00	38	1.82	2	0.37	8.29	0.42
4	12.78	1.01	12	0.92	23	1.93	4	0.56	5.86	0.35
5	10.62	1.04	10	0.94	27	1.92	1	0.52	6.87	0.38
6	14.36	1.09	12	1.12	38	1.81	2	0.64	10.77	0.31
SPI12										
1	13.41	1.01	12	0.85	29	1.92	3	0.47	7.16	0.41
2	15.94	0.99	14	0.98	48	1.66	2	0.56	10.78	0.32
3	13.57	1.13	13	0.94	38	1.97	3	0.58	8.90	0.43
4	19.38	0.98	22	0.91	36	1.66	3	0.42	9.11	0.32
5	13.13	1.12	12	0.90	27	1.90	2	0.42	7.37	0.41
6	17.18	1.12	17	0.99	38	1.91	5	0.59	9.76	0.37
SPI24										
1	25.00	1.00	23	0.94	64	1.47	5	0.56	16.15	0.31
2	30.29	1.01	16	0.86	110	1.34	7	0.80	33.38	0.21
3	19.44	1.05	16	1.05	50	1.91	6	0.58	13.64	0.40
4	47.00	0.96	38	0.98	106	1.20	13	0.80	33.06	0.14
5	23.67	1.07	22	0.85	48	2.03	5	0.80	11.95	0.40
6	22.75	1.24	24	1.19	39	2.13	10	0.78	8.97	0.39
SPEI3										
	4.66	1.09	3	1.08	15	2.27	1	0.51	3.34	0.36
	4.16	1.07	3	1.04	13	1.75	1	0.55	2.66	0.30
	5.50	1.03	3	1.02	28	1.58	1	0.48	5.86	0.25
	4.11	1.06	3	1.01	15	2.19	1	0.51	3.10	0.35
	4.52	1.07	3	1.07	18	1.79	1	0.63	3.85	0.28
	4.14	1.06	3	1.05	15	1.85	1	0.57	2.90	0.29
SPEI6										
	7.14	1.00	5.5	0.91	24	1.78	1	0.56	5.59	0.32
	8.62	1.03	7	1.06	22	1.45	2	0.42	4.95	0.28

Table 3 (continued)

	Average		Median		Max		Min		SD	
	D	*I* (−)	*D*	*I* (−)	*D*	*I* (−)	*D*	*I* (−)	*D*	*I* (−)
	8.92	1.08	6	1.02	40	1.60	1	0.60	8.64	0.31
	8.24	1.02	6	0.97	28	1.97	1	0.60	7.70	0.32
	8.26	0.91	6	0.81	30	1.62	2	0.46	6.31	0.29
	8.35	1.06	7	1.02	24	1.50	2	0.44	5.38	0.28
SPEI9										
	12.21	1.05	10	0.98	25	1.75	2	0.65	6.63	0.30
	10.08	0.99	9	0.92	28	1.77	1	0.48	5.65	0.33
	13.47	1.04	11	1.01	42	1.60	2	0.40	9.84	0.37
	12.74	1.00	10	0.89	36	1.96	4	0.30	8.68	0.41
	10.43	0.98	9	0.94	27	1.87	1	0.48	6.75	0.40
	9.96	1.03	9	0.96	21	1.71	1	0.48	4.80	0.31
SPEI12										
	14.47	1.09	13	1.02	25	1.80	4	0.42	6.07	0.39
	12.25	1.08	8.5	1.11	48	1.58	2	0.52	10.48	0.33
	17.83	1.03	13.5	1.07	52	1.73	5	0.42	13.34	0.43
	18.00	1.10	17	1.06	52	1.70	3	0.58	12.29	0.35
	15.57	1.08	14	0.97	40	1.90	3	0.45	9.87	0.41
	12.67	1.11	10.5	1.10	30	1.57	3	0.68	7.56	0.30
SPEI24										
	19.07	0.99	23	0.96	38	1.63	6	0.55	9.09	0.30
	28.25	1.19	20.5	1.19	102	1.63	1	0.76	28.92	0.29
	36.33	0.80	11.5	0.74	162	1.35	7	0.58	56.33	0.26
	30.14	1.09	20	1.12	74	1.36	4	0.59	26.82	0.24
	32.86	1.02	25	0.96	99	1.72	10	0.66	28.40	0.33
	21.44	1.18	17	1.19	62	1.80	1	0.46	16.42	0.39

*1, Sariyer Kumkoy station; 2, Sariyer station; 3, Kadikoy station; 4, Şile station; 5, Florya station; 6, Kartal station

same at all timescales except at 24 months; drought duration for SPEI was more than the duration obtained based on SPI.

Consistency of SPI and SPEI

The Pearson correlation coefficient (R) is one of the most common ways to estimate the strength of linear correlation between monthly SPI and SPEI for all timescales. The heatmap is a visual impersonation of data utilizing systematic color coding to represent different values. It was used to identify and explain the spatial and temporal variation of linear correlation between SPI and SPEI for specific timescales such as 3, 6, and 12 months; changing in color (from green (1) to brown (0.3)) indicates a change in the R-value (Fig. 6).

Figure 6 shows the correlation coefficient between monthly SPI and SPEI for all stations at 3-, 6-, and 12-month timescale. In the first five stations (Sarıyer Kumköy, Sarıyer, Kadıköy, Şile, and Florya), the R is positive and between 0.65 and 0.98, which is a strong and very strong correlation, respectively. However, the R for the Kartal station was between 0.25 and 0.55, which is a weak and moderate correlation (Irhoumah et al., 2017). This weak correlation can be attributed to the main recorded precipitation and temperature data. The R increased for all stations from January

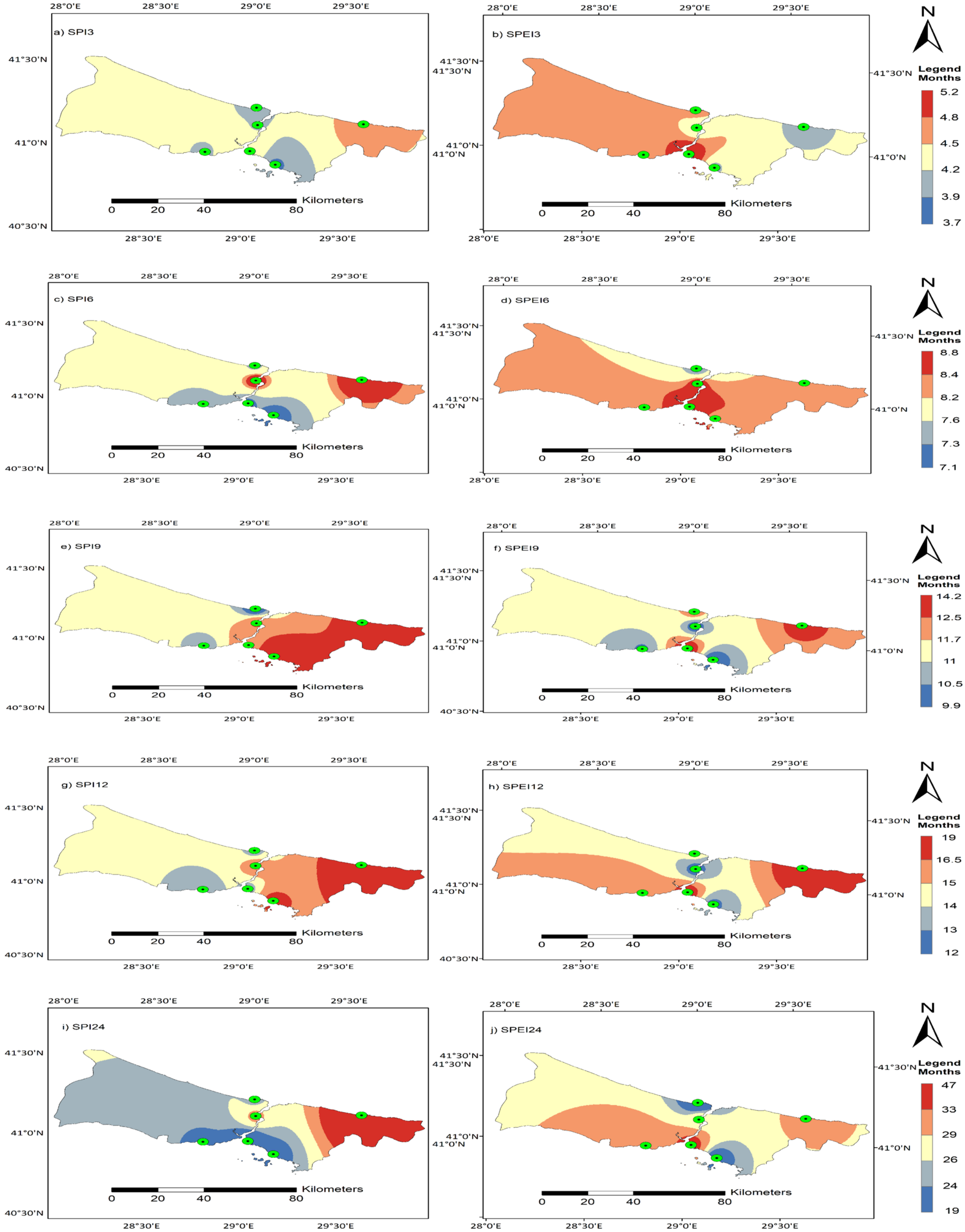


Fig. 4 Spatial distribution of the drought duration (D_month) of SPI and SPEI-based drought events between 1951 and 2020 for Istanbul city: (**a**) SPI 3, (**b**) SPEI 3, (**c**) SPI 6, (**d**) SPEI 6, (**e**) SPI 9, (**f**) SPEI 9, (**g**) SPI 12, (**h**) SPEI 12, (**i**) SPI 24, and (**j**) SPEI 24

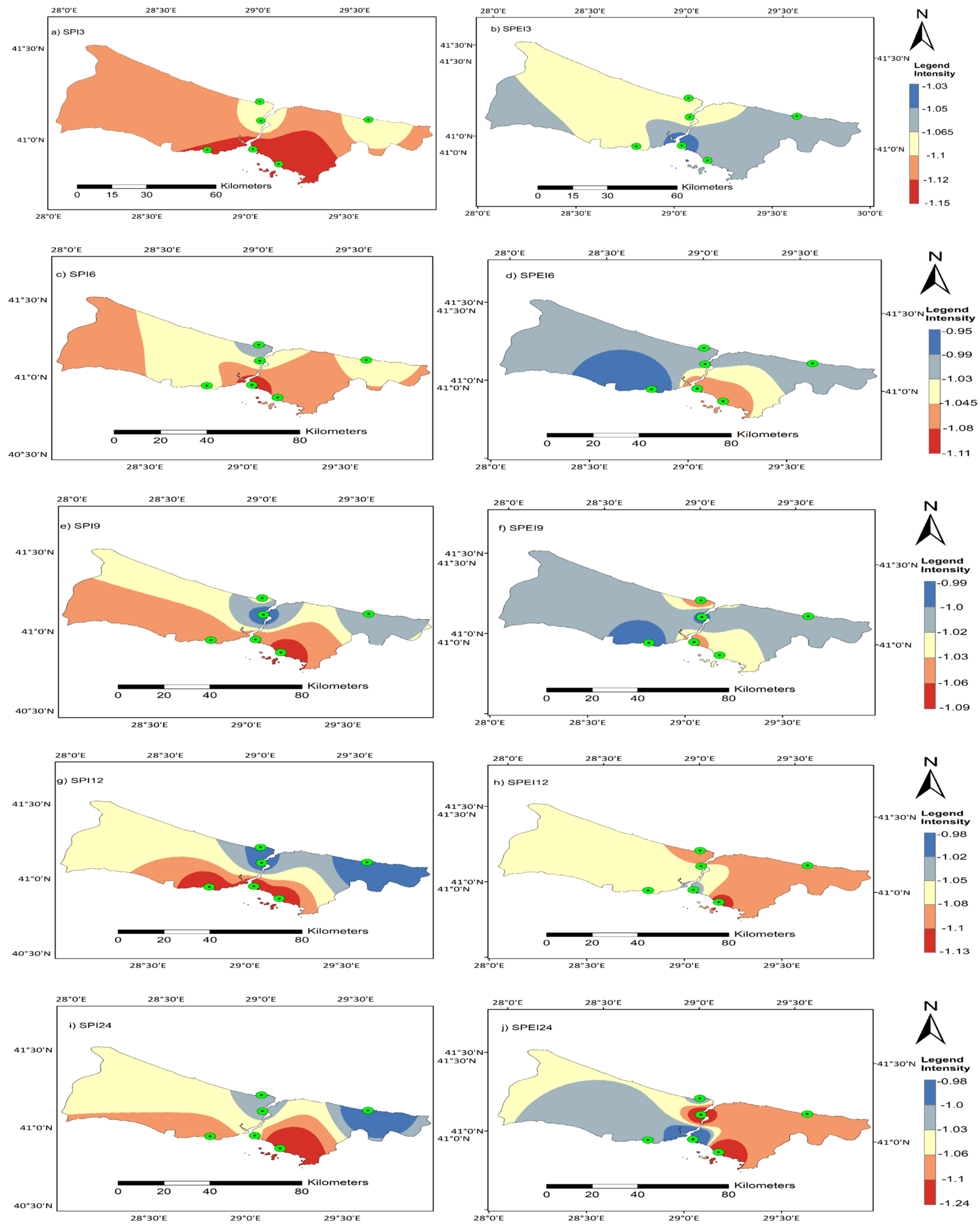


Fig. 5 Spatial distribution of the drought intensity (*I*) of SPI and SPEI-based drought events between 1951 and 2020 for Istanbul city: (**a**) SPI 3, (**b**) SPEI 3, (**c**) SPI 6, (**d**) SPEI 6, (**e**) SPI 9, (**f**) SPEI 9, (**g**) SPI 12, (**h**) SPEI 12, (**i**) SPI 24, and (**j**) SPEI 24

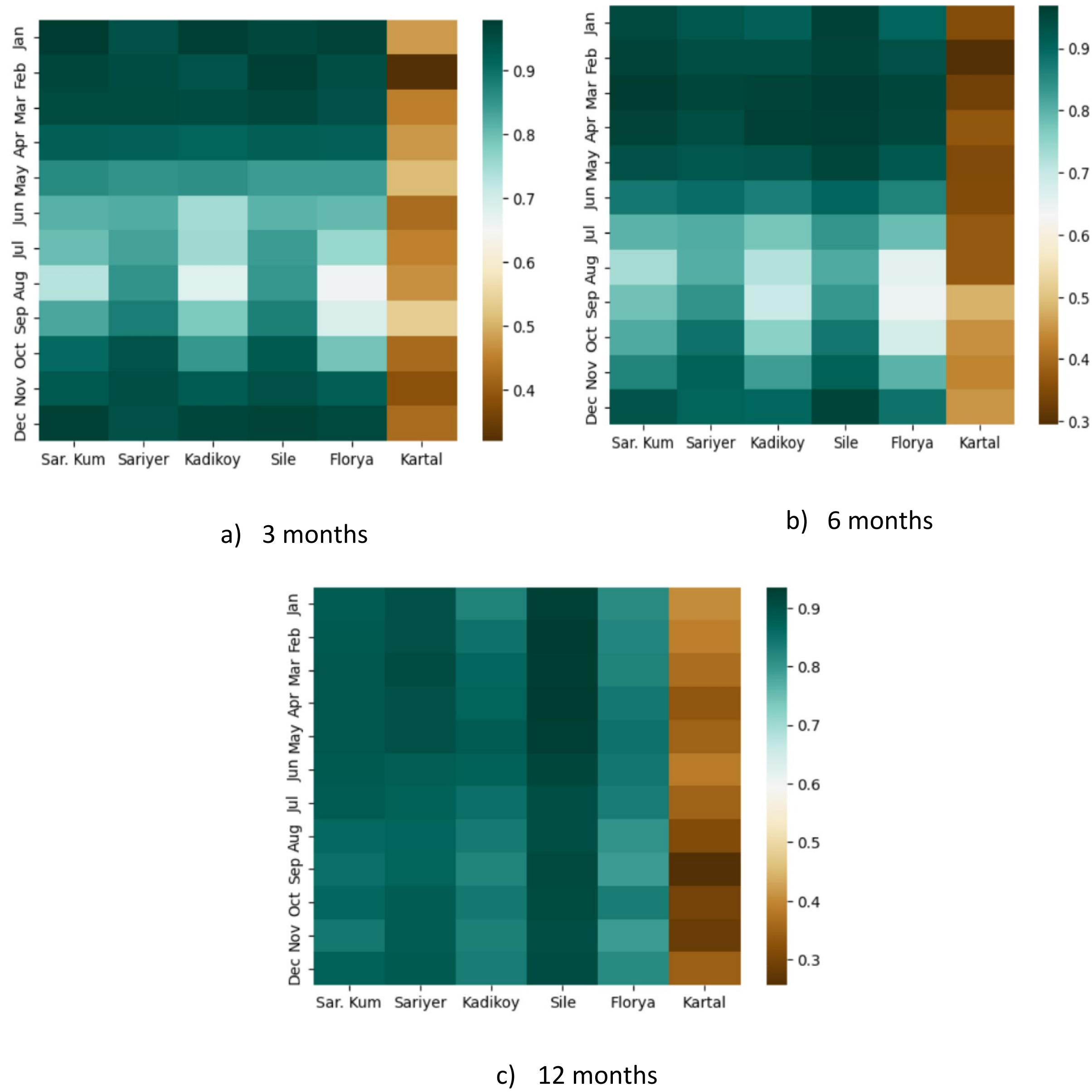


Fig. 6 The correlation coefficient between monthly SPEI and SPI at specific timescales: (**a**) 3 months, (**b**) 6 months, (**c**) 12 months

to May, November, and December. In contrast, the *r* decreased between June and October.

Difference between SPI and SPEI using IDCM

Based on the previous results obtained from the "Consistency of SPI and SPEI" section, the IDCM is applied to Sarıyer and Kartal stations, with the highest and lowest correlation, respectively. IDCM has the power to compare different indices based on drought classification. For short timescales (3 months), the number of months within the same classification was 678 (81%) in Sarıyer station (Fig. 7a). Also, there was only one difference in classification for the remaining months. However, for Kartal station, the number of months was 486 (58%), with two classification differences (Fig. 7b). For the 12-month timescale and Sarıyer station, the number of months was 626 (76%),

SPI 3	SPEI 3_Sarıyer station							
	EW	SW	MW	N	MD	SD	ED	Sum
EW	10	5						15
SW	2	31	8					41
MW		9	66	15				90
N			22	497	34	3		556
MD				24	42	9		75
SD				3	15	24	1	43
ED					3	7	8	18
Sum	12	45	96	539	94	43	9	678 81%

a) SPI 3 and SPEI 3 for Sarıyer station

SPI 3	SPEI 3_Kartal station							
	EW	SW	MW	N	MD	SD	ED	Sum
EW	2	5	4	4				15
SW	2	8	11	15				36
MW	6	9	23	41				79
N	1	25	50	427	61	18	2	584
MD				35	18	14		67
SD				13	15	4	2	34
ED				9	6	4	4	23
Sum	11	47	88	544	100	40	8	486 58%

b) SPI 3 and SPEI 3 for Kartal station

SPI 12	SPEI 12_Sarıyer station							
	EW	SW	MW	N	MD	SD	ED	Sum
EW	5	8						13
SW	1	29	10					40
MW		20	43	22				85
N			39	481	39	2		561
MD				23	40	10		73
SD				3	15	21	4	43
ED						7	7	14
Sum	6	57	92	529	94	40	11	626 76%

c) SPI 12 and SPEI 12 for Sarıyer station

SPI 12	SPEI 12_Kartal station							
	EW	SW	MW	N	MD	SD	ED	Sum
EW	4	3	2	2				11
SW	2	11	13	21				47
MW		9	10	37				56
N	1	32	58	430	58	11	6	596
MD				26	21	7	6	60
SD			1	11	12	13	2	39
ED				10	5	1	4	20
Sum	7	55	84	537	96	32	18	493 55%

d) SPI 12 and SPEI 12 for Kartal station

Fig. 7 Difference between SPI and SPEI for Sarıyer and Kartal stations using IDCM (Abu Arra & Şişman, 2024): (**a**) SPI 3 and SPEI 3 for Sarıyer station, (**b**) SPI 3 and SPEI 3 for Kartal station, (**c**) SPI 12 and SPEI 12 for Sarıyer station, and (**d**) SPI 12 and SPEI 12 for Kartal station

and for Kartal station, it was 493 (55%). Most months are located within this category because of the high range of the normal category_N (−1 to 1).

Difference between SPEI from meteorological stations and SPEIbase

As can be noticed in Fig. 1, the number of gridded data is limited because of the large scale of the data. The first three meteorological stations (Sarıyer Kumköy, Sarıyer, and Kadıköy) are located on the same grid. Each Florya, Şile, and Kartal station is located on a different grid. The comparison between them was conducted through two different approaches. The first approach is based on SPEI classification using IDCM, proposed by Abu Arra and Şişman (2024) (Table 2). The second approach is plotting the difference between the drought index for both meteorological stations and the SPEI database.

Figure 8 shows the number of months that belong to a specific drought classification according to SPEI3 calculated using meteorological stations (column 1) and a specific drought classification based on the SPEI database (row 1). The common categories are shown by shaded cells. The blue cell is the total number and percentage of the same drought categories for each station. The empty cells are cells without any month. According to Fig. 8, the same classification percentage is about 58%. For Sarıyer Kumköy, 8 of the months gave severe drought (SD) based on the station and normal (*N*) based on the SPEI database. For the Şile station, 1 month was severe drought (SD) based on the station and severe wet (SW) based on the SPEI database. Despite each classification having a wide range of DI, it can be noticed that there is a significant difference between stations and the SPEI database. The sum in Fig. 8 gives the summation for each drought classification.

The difference between SPEI at a 12-month timescale is summarized in Fig. 9. The percentage of months with the same drought classification was about 62%, more than the percentages for SPEI3.

		SPEI 3_SPEI_database_Grid							
		EW	SW	MW	N	MD	SD	ED	Sum
SPEI 3_Station	EW	9	2	0	2	0	0	0	13
	SW	13	28	8	6	1	0	0	56
	MW	5	19	19	28	1	0	0	72
	N	3	17	57	410	62	10	3	562
	MD	0	0	0	30	28	22	3	83
	SD	0	0	0	8	12	12	6	38
	ED	0	0	0	2	1	5	6	14
	Sum	30	66	84	486	105	49	18	512 61%

a) Sarıyer Kumköy station

		SPEI 3_SPEI_database_Grid							
		EW	SW	MW	N	MD	SD	ED	Sum
SPEI 3_Station	EW	6	3	2	1	0	0	0	12
	SW	9	11	5	20	0	0	0	45
	MW	8	33	19	34	2	0	0	96
	N	7	19	58	393	51	9	2	539
	MD	0	0	0	32	36	24	2	94
	SD	0	0	0	6	16	13	8	43
	ED	0	0	0	0	0	3	6	9
	Sum	30	66	84	486	105	49	18	484 58%

b) Sarıyer station

		SPEI 3_SPEI_database_Grid							
		EW	SW	MW	N	MD	SD	ED	Sum
SPEI 3_Station	EW	9	6	1	0	0	0	0	16
	SW	11	16	6	10	0	0	0	43
	MW	5	20	26	35	0	0	0	86
	N	7	20	46	390	58	15	1	537
	MD	0	4	5	35	35	15	6	100
	SD	0	0	0	10	11	15	7	43
	ED	0	0	0	1	4	2	6	13
	Sum	32	66	84	481	108	47	20	497 59%

c) Kadıköy station

		SPEI 3_SPEI_database_Grid							
		EW	SW	MW	N	MD	SD	ED	Sum
SPEI 3_Station	EW	10	3	4	0	0	0	0	17
	SW	11	13	7	7	0	0	0	38
	MW	2	22	24	42	0	0	0	90
	N	8	25	59	383	63	23	1	562
	MD	0	0	4	37	24	18	2	85
	SD	0	1	0	9	10	5	8	33
	ED	0	0	0	3	4	1	5	13
	Sum	31	64	98	481	101	47	16	464 55%

d) Şile station

		SPEI 3_SPEI_database_Grid							
		EW	SW	MW	N	MD	SD	ED	Sum
SPEI 3_Station	EW	6	7	1	2	0	0	0	16
	SW	8	18	13	5	0	0	0	44
	MW	10	17	25	43	0	0	0	95
	N	7	22	55	383	55	11	1	534
	MD	0	0	3	39	35	19	4	100
	SD	0	0	1	9	9	12	7	38
	ED	0	0	0	0	2	5	4	11
	Sum	31	64	98	481	101	47	16	483 58%

e) Florya station

		SPEI 3_SPEI_database_Grid							
		EW	SW	MW	N	MD	SD	ED	Sum
SPEI 3_Station	EW	6	3	2	0	0	0	0	11
	SW	11	8	8	20	0	0	0	47
	MW	7	28	26	27	0	0	0	88
	N	7	25	62	395	46	8	1	544
	MD	0	0	0	36	36	25	3	100
	SD	0	0	0	3	18	13	6	40
	ED	0	0	0	0	1	1	6	8
	Sum	31	64	98	481	101	47	16	490 59%

f) Kartal station

Fig. 8 The difference between SPEI from stations and SPEI-base at a 3-month timescale: (**a**) Sarıyer Kumköy station, (**b**) Sarıyer station, (**c**) Kadıköy station, (**d**) Şile station, (**e**) Florya station, and (**f**) Kartal station. The shaded cells indicate the same drought classifications. The blue color indicates the number and percentage of the same drought classifications

The months with normal (*N*) classification for meteorological stations was more than the SPEI database, and it was at 440 at Florya station. Also, the Şile station has an opposite situation at a large timescale; for example, it was SW at the SPEI database and SD and ED at the meteorological station. The maximum number of (ED) months was at Şile station. For both SPEI3 and SPEI12 for all stations, it can be noted that the normal classification is the dominant classification with 45–50% of all months. This is attributed to the fact that the normal classification ranges widely between – 1 and 1.

		SPEI 12_SPEI_database_Grid							
		EW	SW	MW	N	MD	SD	ED	Sum
SPEI 12_Station	EW	9	0	5	0	0	0	0	14
	SW	12	23	9	4	0	0	0	48
	MW	5	23	15	37	1	0	0	81
	N	11	10	44	446	34	8	1	554
	MD	0	0	1	23	27	15	3	69
	SD	0	0	0	6	8	26	13	53
	ED	0	0	0	0	0	6	4	10
	Sum	37	56	74	516	70	55	21	550 66%

a) Sarıyer Kumköy station

		SPEI 12_SPEI_database_Grid							
		EW	SW	MW	N	MD	SD	ED	Sum
SPEI 12_Station	EW	2	1	3	0	0	0	0	6
	SW	21	12	8	16	0	0	0	57
	MW	3	23	15	51	0	0	0	92
	N	11	20	47	402	35	14	0	529
	MD	0	0	1	37	27	22	7	94
	SD	0	0	0	10	8	12	10	40
	ED	0	0	0	0	0	7	4	11
	Sum	37	56	74	516	70	55	21	474 57%

b) Sarıyer station

		SPEI 12_SPEI_database_Grid							
		EW	SW	MW	N	MD	SD	ED	Sum
SPEI 12_Station	EW	11	6	1	0	0	0	0	18
	SW	13	21	4	8	0	0	0	46
	MW	2	13	11	41	0	0	0	67
	N	11	15	45	434	47	14	2	568
	MD	0	0	7	11	8	24	6	56
	SD	0	1	6	17	11	14	7	56
	ED	0	0	0	5	4	3	6	18
	Sum	37	56	74	516	70	55	21	505 61%

c) Kadıköy station

		SPEI 12_SPEI_database_Grid							
		EW	SW	MW	N	MD	SD	ED	Sum
SPEI 12_Station	EW	13	9	3	0	0	0	0	25
	SW	9	3	2	2	0	0	0	16
	MW	4	23	32	43	0	0	0	102
	N	9	12	53	420	52	17	3	566
	MD	1	0	2	27	15	13	3	61
	SD	1	1	0	10	3	12	9	36
	ED	0	3	2	6	4	4	4	23
	Sum	37	51	94	508	74	46	19	499 60%

d) Şile station

		SPEI 12_SPEI_database_Grid							
		EW	SW	MW	N	MD	SD	ED	Sum
SPEI 12_Station	EW	11	2	1	1	0	0	0	15
	SW	7	14	16	8	0	0	0	45
	MW	8	14	18	26	0	0	0	66
	N	11	19	57	440	38	10	0	575
	MD	0	2	0	26	15	13	10	66
	SD	0	0	2	7	15	12	2	38
	ED	0	0	0	0	6	11	7	24
	Sum	37	51	94	508	74	46	19	517 62%

e) Florya station

		SPEI 12_SPEI_database_Grid							
		EW	SW	MW	N	MD	SD	ED	Sum
SPEI 12_Station	EW	3	1	3	0	0	0	0	7
	SW	20	11	7	17	0	0	0	55
	MW	3	22	24	35	0	0	0	84
	N	11	17	58	414	34	3	0	537
	MD	0	0	2	39	32	20	3	96
	SD	0	0	0	3	7	17	5	32
	ED	0	0	0	0	1	6	11	18
	Sum	37	51	94	508	74	46	19	512 62%

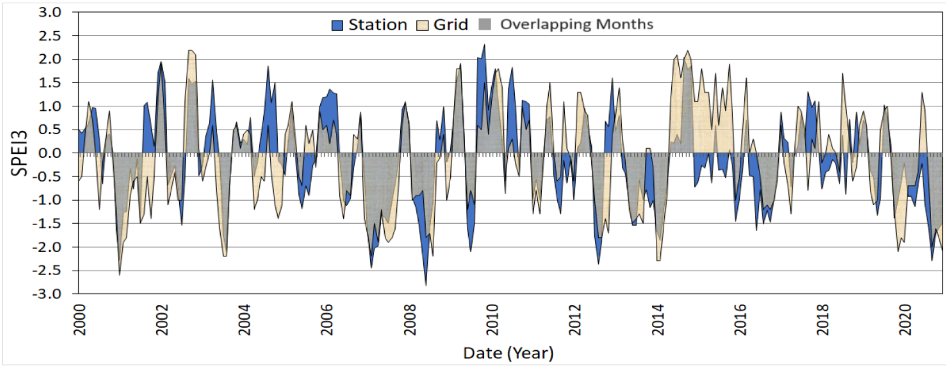
f) Kartal station

Fig. 9 The difference between SPEI from stations and SPEI-base is at a 12-month timescale: (**a**) Sarıyer Kumköy station, (**b**) Sarıyer station, (**c**) Kadıköy station, (**d**) Şile station, (**e**) Florya station, and (**f**) Kartal station. The shaded cells indicate the same drought classifications. The blue color indicates the number and percentage of the same drought classifications

Figure 10 and Fig. 11 show the detailed difference between SPEI3 and SPEI12 from meteorological stations and the SPEI database for the last 20 years (2000–2020). The blue area is the drought index values from stations, the yellow is the drought index from grid data, and the gray is the overlapping months. For SPEI3 at Sriyer Kumköy, Şile, Florya, and Kartal stations, the SPEI values demonstrated significant consistency, showing very similar and closely aligned SPEI values each month until 2015. However, they exhibited a stark contrast in the last 5 years (after 2015), with the same months displaying

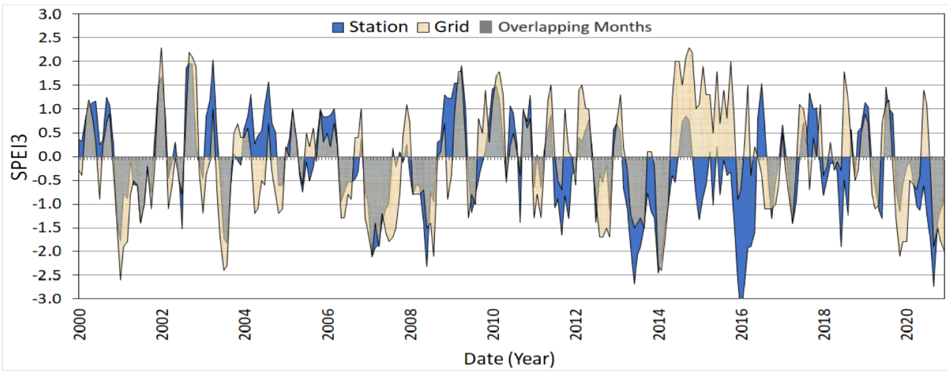
a) SPEI 3

Sarıyer Kumköy Station.



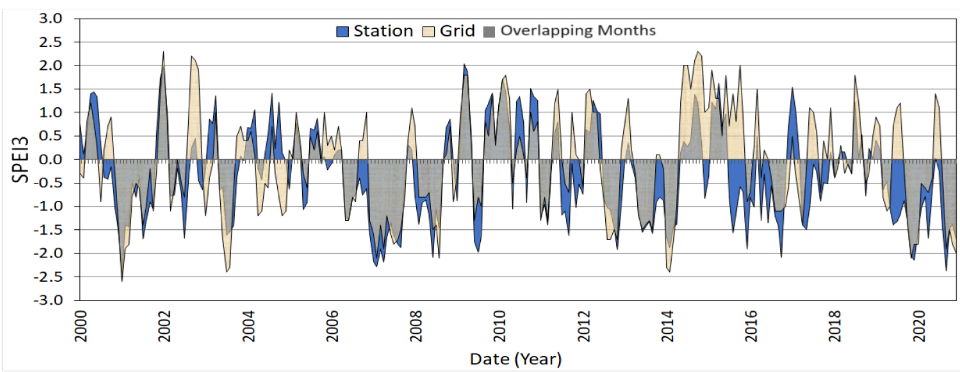
b) SPEI 3

Şile Station.



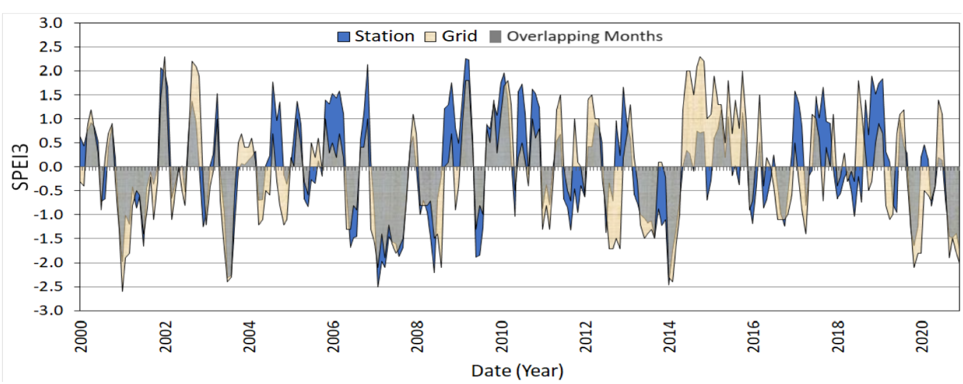
c) SPEI 3

Florya station.



d) SPEI 3

Kartal Station.



◂**Fig. 10** The comparison between SPEI3 from the meteorological station and SPEI database using drought indices for the last 20 years: (**a**) Sarıyer Kumköy station, (**b**) Şile station, (**c**) Florya station, and (**d**) Kartal station

both wet and dry conditions. This indicated a significant variability in the SPEI over this time period. For example, in 2016 at Şile station, the SPEI3 from the station was − 3.0; from the grid, it was 1.5 in the same month. In Florya station, in 2019, the SPEI3 from the station was − 1.5; from the grid, it was 1.25. The SPEI3 values were exactly the same in Kartal station between 2006 and 2008.

For SPEI12, the differences can be noticed more clearly. In Şile, the SPEI12 was different between 2015 and 2017. In the same months, it was dry and wet. In Florya station, SPEI12 was approximately the same between 2007 and 2011. Figure 10 and Fig. 11 depict the differences between SPEI3 and SPEI12 from the meteorological stations and SPEI database in detail.

Discussion

The temporal and spatial evaluation of drought is paramount in effective water resources management, impacting various sectors and aspects of human life (Tigkas et al., 2019). The initial step in this evaluation is the calculation of drought index, with the SPI and SPEI emerging as commonly used and accepted indices (WMO 2012). Each index, however, comes with assumptions and mathematical equations, necessitating a comprehensive and detailed assessment (Abu Arra et al., 2024b; Laimighofer & Laaha, 2022). The literature underscores the significance of understanding the distinctions between SPI and SPEI regarding drought index performance, associated characteristics, and classifications. This evaluation is essential for ensuring the selection of the most suitable index for a given context, providing a foundation for robust drought analyses and informed decision-making in water resource management. There were many differences between SPEI and SPI in regional drought evaluation and monitoring that can be found in several studies, such as Liu et al. (2016), Soydan Oksal (2023), Laimighofer and Laaha (2022), and Nwayor and Robeson (2023). Due to the definition of each DI and differences in climatic conditions, there are differences between SPI and SPEI, and the applicability and the differences between SPI and SPEI have been discussed in a new framework in this study.

There are many drought indices, and a continuous effort to derive the most efficient ones for better monitoring and assessment based on specific purposes is very useful and necessary for early warning. This research indicates that most of Istanbul has suffered from drought, especially in the last 20 years, which agreed with the outcomes of the IPCC report (IPCC, 2022). Also, it is important due to the lack of water resources in Istanbul (ISKI, 2023). Based on the results obtained, the number of drought events increased; the most prolonged drought events were observed during the previous 20 years, agreeing with the study done by Soydan Oksal (2023), leading to the lowest percentage of the dam's fullness within the last 15 years. The drought duration increases with increasing timescale. For example, the drought duration of SPEI24 at station Şile was 74 months, between October 2012 and November 2018, with average drought intensity equal to − 1.4 (Table 3). This can be attributed to the concept of using different timescales, which are based on the summation of 3, 6, etc. months. Regarding spatial distribution, higher drought duration and intensity have been noticed in the southeastern and northern parts of Istanbul (see Fig. 4 and Fig. 5).

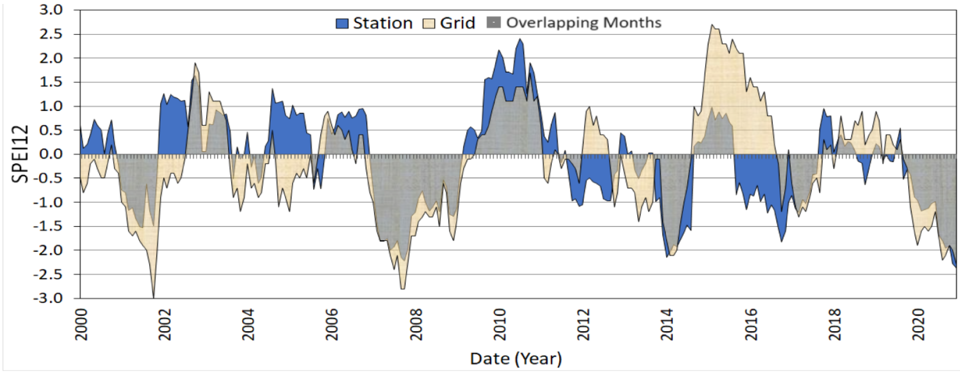
In literature, the SPI and SPEI were calculated based on drought index and rarely on drought characteristics, and none of these studies considered drought classification in the comparison process. Firstly, based on the drought index, the correlation coefficient between SPI and SPEI was calculated for the drought event scale and monthly scale, which is the main point in the comparison process. The correlation coefficient was positive and strong, which is similar to the results obtained by Mathbout et al. (2018). Also, the correlation coefficient between SPI and SPEI on a monthly scale was highly correlated for all stations (more than 0.65). In areas with lower correlation coefficients, selecting one of SPI and SPEI is more significant, and the decision must be taken regarding different aspects, such as the amount of precipitation and evapotranspiration (Laimighofer & Laaha, 2022).

Regarding drought characteristics, Table 3 shows no consistent relationship between SPI and SPEI at the drought event scale. SPI has a more extensive

a) SPEI 12

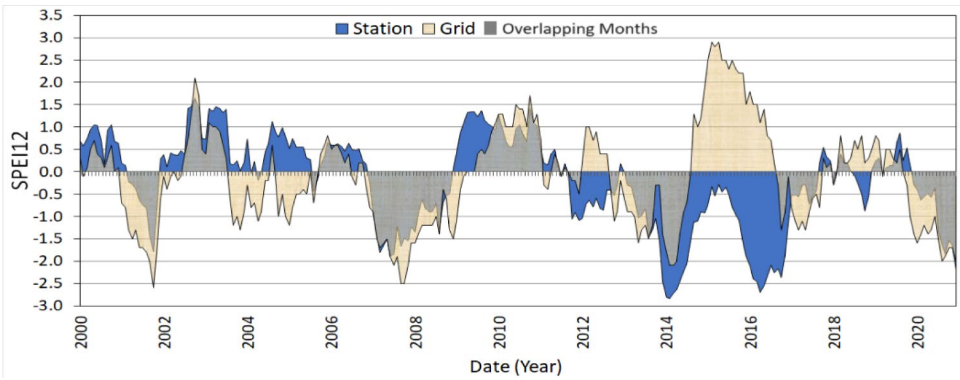
Sarıyer Kumköy

Station.



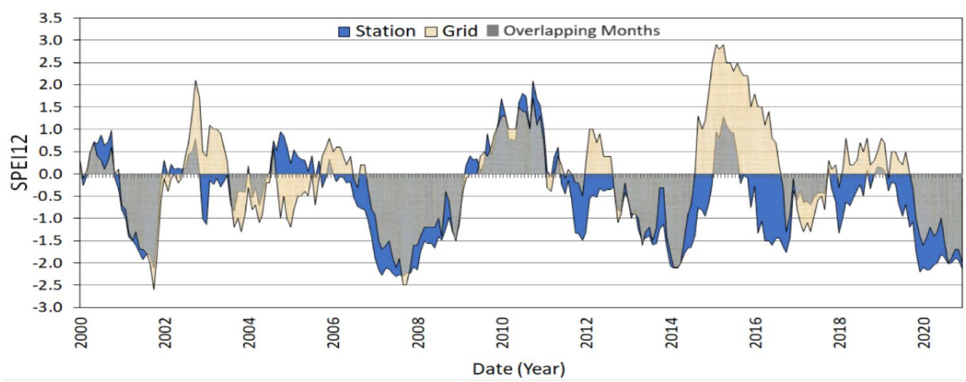
b) SPEI 12

Şile Station.



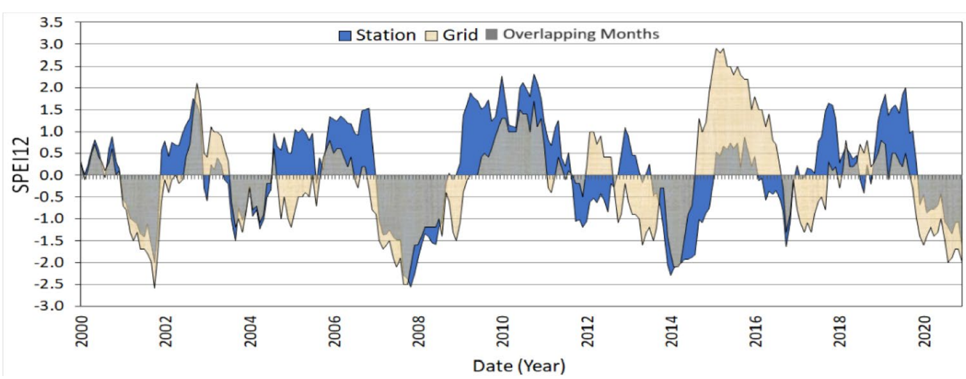
c) SPEI 12

Florya station.



d) SPEI 12

Kartal Station.



◂**Fig. 11** The comparison between SPEI12 from the meteorological station and SPEI database using drought indices for the last 20 years: (**a**) Sarıyer Kumköy station, (**b**) Şile station, (**c**) Florya station, and (**d**) Kartal station

duration and intensity at some stations and specific timescales. At the same time, in other instances, the SPEI may be the dominant drought index to calculate the drought characteristics, which is consistent with other research results (Tirivarombo et al., 2018). This is not referred only to the effect of PET related to SPEI but also to the fitted PDF (gamma function for SPI, and log-logistic for SPEI) resulting for each drought index, and consequently, a difference in drought characteristics is expected. Also, a considerable increase in drought events, duration, and severity has been identified after 1999. The increase in drought events, duration, and severity after 1999 is attributed to the increase in temperature, which is discussed in IPCC (2022) and SDGs. In accordance with the findings of Mathbout et al. (2018), drought severity and duration heightened with an increase in timescale, and the SPEI exhibited a capacity to identify prolonged and more intense drought events when compared to the SPI. In alignment with these outcomes, the present study finds that as the timescale increased. Eris et al. (2020) conducted a study encompassing temporal and spatial analyses of meteorological drought and dry periods within the Kucuk Menderes River Basin in western Türkiye from 1960 to 2018. The investigation employed the SPI and SPEI to assess meteorological drought across short- and long-term timescales. The outcomes revealed the reliability of short-term timescales for both SPI and SPEI indices.

Drought classification plays a crucial role in comprehensively understanding and effectively managing the impacts of drought events. Despite the paramount importance of this aspect, previous studies comparing SPI and SPEI often overlooked the significance of employing a systematic drought classification methodology. This study addressed this gap by utilizing the IDCM to compare drought classifications between SPI and SPEI. The outcomes revealed that approximately 60% of the months exhibited consistent drought classifications between the two indices. This finding underscores the importance of incorporating drought classification in drought assessments and validates the coherence between the two indices, as supported by the correlation coefficient results. Including a robust classification framework adds depth to the comparison, offering valuable insights for improved drought characterization and management strategies (Abu Arra and Şişman 2024).

One of the most added values in this research is considering both in situ meteorological stations and the SPEI database (satellite data) and investigating their differences. In cases of small numbers of stations and small-scale areas like Istanbul, the question was, which is better to use? This question was answered in two approaches. The first one is regarding drought classifications defined by McKee et al. (1993), and the second approach used the SPEI values. Figure 8 and Fig. 9 show that the percentage of months with the same drought classification was about 60%, indicating a considerable disparity between them. Furthermore, SPEI3 and SPEI12 calculated using in situ meteorological stations gave more MD, SD, and ED events than the SPEI database. This can be attributed to three reasons: (1) the time period differed. For meteorological stations, it was 70 years. But for the SPEI database, it was about 120 years. (2) The method used for PET was not the same; for stations, the Thornwaite was used. And for the SPEI database, the Panmen-Mointeith method was used (Tirivarombo et al., 2018; Berhail & Katipoğlu, 2023). (3) The reliability of precipitation records for the SPIE database and the large area (3080 km^2) covered by one grid. Three in situ stations are located in the same grid, and there is a vital difference between these stations and the grid data, which indicates that using this large scale may lead to less reliability in the results obtained (Sırdaş and Şen 2001). The change in the SPI and SPEI values at the observational stations leads to the differences in the spatiotemporal assessment. The differences in SPI and SPEI values result in variations in drought events and characteristics. For example, while the average drought duration based on SPI3 at the Sarıyer Kümkoy station was 4 months, the average drought duration based on SPEI was approximately 4.5 months. These differences in values directly impact the spatiotemporal outcomes, as observed in the varying drought events and durations across the study area. In summary, the differences in the spatiotemporal maps are due to the variations in SPI and SPEI values.

This research offers a substantial contribution to the field, providing valuable insights that can be directly applied by decision-makers, water resources managers, and various utilities involved in drought assessment. The obtained results hold practical significance, enabling a comprehensive evaluation of drought conditions. Decision-makers can particularly benefit from identifying the longest drought durations, aiding in strategic planning for water supply and demand scenarios. Utilizing the IDCM in our study further enhances the reliability of the results, establishing a robust foundation for both our findings and potential integration into broader drought assessment studies. This research thus serves as a valuable resource for stakeholders seeking informed strategies to address the challenges posed by drought events.

A limitation of this research lies in the uneven distribution of long and continuous datasets over the study area, coupled with significant data gaps in large areas lacking in situ meteorological stations. The spatial resolution of the SPEI database, set at 0.5°, further amplifies this limitation. While acknowledging this constraint, it is essential to note that the potential impact on the reliability of our results is mitigated by the methodology employed. The comparison processes, integral to the study, are conducted point by point, allowing for a focused assessment that minimizes the influence of data distribution irregularities. To enhance the robustness of future studies, we recommend considering alternative global precipitation and temperature products validated for their applicability to diverse climate and drought studies.

Conclusion

Analyzing the performance and differences between SPI and SPEI based on drought index, characteristics, and classification allows a more comprehensive understanding of the drought dynamics. Also, because of the data availability challenges, particularly for developing countries, there is a need to select one drought index. The comparison process covered short, medium, and long timescales over Istanbul between 1951 and 2020. For the first time, this research considered the drought classification using the IDCM for comparison. The results obtained from in situ meteorological stations and the SPEI_database product were compared, leading to an investigation of the effect of the data source used. The main conclusions of this research are summarized below:

1- The outcomes show extreme drought events in the last 20 years (from 2000) at all timescales, with high drought duration and intensity, leading to the lowest dam's emptiness rate for the last 15 years.

2- Comparison between SPI and SPEI is essential for ensuring the selection of the most suitable index for a given context, providing a foundation for robust drought analyses and informed decision-making in water resource management.

3- Based on the drought index, the correlation coefficient between SPI and SPEI was calculated for the drought event scale and monthly scale. The results show a strong relationship between them (more than 0.65).

4- This research addressed the gap of not considering drought classification by utilizing the IDCM to compare drought classifications between SPI and SPEI. The outcomes revealed that approximately 60% of the months fell within the same classifications.

5- In data availability challenges, this research tried to solve the difference between in situ meteorological stations and satellite data (grid), which can be used as an alternative data source. The results show a significant difference between SPEI based on in situ meteorological stations and satellite data. For example, for drought classifications, only 60% of the months are within the same classification. And for the last 20 years, figures depict a dominant difference.

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Author contribution Ahmad Abu Arra: Conceptualization; Formal analysis; Investigation; Methodology; Resources; Software; Visualization; Roles/Writing—original draft; Writing—review & editing.; Eyüp Şişman: Conceptualization; Data curation; Formal analysis; Methodology; Project administration; Supervision; Validation; Writing—original draft; Writing—review & editing.

Data availability All data that support this study's findings are available from the corresponding author upon reasonable request. The SPEI data are available at SPEI database. https://spei.csic.es/database.html. (Accessed on 20 June 2023).

Declarations

Ethical approval Compliance with ethical standards.

Consent to participate Not applicable.

Consent for publication Not applicable.

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