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Meteorological Drought Analysis Using Multiple Indices for Selected Stations in Iraq

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Keywords:
China-Z Index; Modified CZI; Standardized Precipitation Index; Drought Index; Iraq; Meteorological Drought.

Highlights:

- *Study the characteristics of meteorological drought in Iraq using SPI, CZI, and MCZI on various timescales.*
- *Selected stations in Iraq according to Köppen climate classification, which are Dukan, Kirkuk, Baiji, Rutba, and Basra.*
- *Using monthly precipitation data from 1980 to 2021.*
- *MCZI showed wetness earlier than SPI, CZI.*
- *CZI described the drought as having less severity than SPI, overall CZI can be considered good indices for describing drought in all regions of Iraq.*

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Abstract: This study aims to assess the performance of three drought indices for drought monitoring to study the characteristics of meteorological drought in Iraq, which are the Standard Precipitation Index (SPI), the China-Z Index (CZI), and the Modified China-Z Index (MCZI) on 1-, 3-, 6-, 9-, and 12-month timescales, using monthly precipitation data from 1980 to 2021. These indices were used to analyze the spatiotemporal dynamics of droughts using the rainfall data collected from five meteorological stations scattered across the four climatic zones as classified by Köppen in Iraq. According to the study, the Pearson correlation coefficient (r) values among the indices increase with increasing time scale and give similar drought characteristics at the 9-month and 12-month time scales. SPI generally indicated the drought event earlier and with more severe characteristics than the other indices. MCZI showed wetness earlier than the other two indices, and it also described the drought categories similarly to SPI and CZI, especially in the northern regions of Iraq, but it was less official in describing it as we headed down to the south. While CZI described the drought as having less severity than SPI, it frequently gives the same classifications of drought as SPI. CZI could be used as a good meteorological drought monitor, depending on the month, the length of the drought duration, and the climatic conditions of the region. It might be an alternative to the SPI, which needs long rainfall records and has a complicated structure. SPI and CZI can be considered good indices for describing drought in all regions of Iraq. The result shows that 1980, 1993, 1995, and 2019 were the most wet years; 2007–2010 was the most severe drought event; and Iraq's climate was normal to moderate drought during the studied period for all considered stations.

تحليل الجفاف المناخي باستخدام مؤشرات متعددة لمحطات مختارة في العراق

سيونج رمزي علي قزانجي، تيمور عبد المجيد ابراهيم آوجي
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الخلاصة

تهدف هذه الدراسة إلى تقييم أداء ثلاثة مؤشرات جفاف لرصد الجفاف ولدراسة خصائص الجفاف المناخي في العراق، وهي: مؤشر هطول الأمطار القياسي(SPI) ، مؤشر Z الصيني (CZI)، ومؤشر Z الصيني المعدل (MCZI) وفق فترات زمنية ١ و٣ و٦ و٩ و١٢ شهرا، باستخدام بيانات هطول الأمطار الشهرية من ١٩٨٠ إلى ٢٠٢١. تم استخدام هذه المؤشرات لتحليل الديناميكية الزمانية المكانية للجفاف باستخدام بيانات هطول الأمطار التي تم جمعها من خمس محطات أرصاد جوية منتشرة في المناطق المناخية الأربعة حسب تصنيف Köppen في العراق. ووفقا للدراسة، فإن قيم معامل ارتباط بيرسون (r) بين المؤشرات تزداد مع زيادة النطاق الزمني وتعطي خصائص جفاف مماثلة في النطاقين الزمنيين ٩ أشهر و١٢ شهرا. واظهر مؤشر SPI الجفاف في وقت مبكر وبخصائص أكثر حدة من المؤشرين الاخرين. بينما أظهر MCZI الرطوبة في وقت أبكر من المؤشرين الآخرين، كما وصف فئات الجفاف بشكل مشابه ل SPI وCZI، خاصة في المناطق الشمالية من العراق، لكنه كان أقل ارتباطا بالمؤشرين في وصفه للجفاف عندما اتجهنا إلى الجنوب. في حين وصفت CZI الجفاف بأنه أقل حدة من SPI، فإنه غالبا ما يعطي نفس تصنيفات الجفاف مثل SPI. يمكن استخدام CZI كمراقب جيد للجفاف في الأرصاد الجوية، اعتمادا على الشهر وطول مدة الجفاف والظروف المناخية للمنطقة. قد يكون بديلا ل SPI، الذي يحتاج إلى سجلات هطول أمطار طويلة وله هيكل معقد حسابيا. يمكن اعتبار SPI وCZI مؤشرات جيدة لوصف الجفاف في جميع مناطق العراق. تظهر النتيجة أن السنوات ١٩٨٠ و١٩٩٣ و١٩٩٥ و٢٠١٩ كانت أكثر السنوات رطوبة. وكانت الفترة ٢٠٠٧-٢٠١٠ أشد فترة جفاف خلال فترة الدراسة. وأن مناخ العراق كان طبيعيا إلى معتدل الجفاف خلال الفترة المدروسة ولجميع المحطات المدروسة.

الكلمات الدالة: مؤشر الصين-Z؛ تعديل تشيكوسلوفاكيا. مؤشر الهطول الموحد؛ مؤشر الجفاف؛ العراق؛ الجفاف الجوي.

1.INTRODUCTION

Droughts are the second most costly weather crisis after hurricanes [1]. Each year, drought negatively impacts millions of people and costs the world billions of dollars [2]. In 2021, 40% of the world was suffering from drought, and with the exacerbation of water shortages, there is a possibility of a mass migration of residents from the dry zones in search of water [3]. Drought is classified into four types based on the stage of its occurrence: meteorological, agricultural, hydrological, and socio-economic. meteorological drought occurs when precipitation is less than normal, while agricultural drought occurs when soil moisture and precipitation are insufficient for crop growth. Hydrological drought results from a persistent lack of water resources. Socio-economic drought is the combination of meteorological, hydrological, and agricultural droughts, influenced by weather and supply and demand processes [4] . Drought was defined by meteorologists as a lengthy period of dry weather caused by a lack of precipitation, resulting in severe water scarcity for some activities, populations, or ecological systems. Drought may also be defined with accuracy as a long-term imbalance between precipitation and evaporation [5]. Drought is negatively affecting the whole area of Iraq, and its dangers are exacerbated every day with fluctuating rainfall during the winter and its scarcity the rest of the year. In addition to that, the ability of the population to deal with and adapt to drought is very limited. Iraq is suffering recently from a negative trend in rainfall with severe drought conditions, which has led to a negative impact on water levels, agricultural production, the biomass of pastures, and migration from rural areas [6]. Farming communities in Iraq have experienced that wheat, barley, vegetable, and fruit harvests have fallen year after year in a row owing to severe drought conditions, leaving people exposed to diminishing earnings and food insecurity [7]. The year 2022 is one of the harshest drought years that Iraq has experienced since 1930, with the percentage of water storage declining by more than 60% compared to previous years [8]. The Euphrates and Tigris River discharges, which supply 98% of Iraq's surface water, have decreased by 30%–40% during the previous 40 years [9]. The southern Marshes wetland, a natural treasure, is also drying up. Iraq is warming; with Basra reaching 54C^0in 2022, seawater floods southern areas like Shatt Al-Arab, damaging crops [10]. All of these facts lead to and encourage more research into the characteristics of the drought, as well as attempts to predict its onset and termination in order to mitigate its hazards and losses. It grows slowly, which makes the accurate determination of the onset time of drought difficult, but usually drought indices are used to estimate the severity and duration of drought. Drought monitoring and prediction are hence vital for natural resource management in semiarid and arid parts of the world [11]. drought indices reflect a variety of events and situations; they could reflect climatic dryness anomalies (mostly based on precipitation) or delayed agricultural and hydrological implications such as soil moisture loss or decreased reservoir levels. Moreover, drought indices can be classified based on the data and technology employed. A significant number of indices, for example, use remote-sensing images to assess vegetation health as a drought indicator [12]. Over the years, more than 150 drought indices have been developed [13]. The use of these indices depends on many climatic parameters such as temperature, humidity, precipitation, winds and ocean currents, solar radiation, topography, latitude, and elevation, but precipitation is the most important input in determining the severity of the drought [14]. Fortunately, data for long periods are widely available from the meteorological ground station or from some of the available websites, e.g., the NASA Power (data access viewer) website (https://power.larc.nasa.gov/). Many of these indices are shown in the literature, e.g., the Effective Drought Index (EDI) [15], the Surface Water Supply Index (SWSI) [16], and the China-Z index (CZI), which is utilized by the National Metrological Centre of China [17]. The Standardized Precipitation Index (SPI), which has garnered international recognition [18], and all of the DI are derived from climatic data on rainfall. No index is perfect or generally applicable [15]. The selection of suitable indices for drought monitoring in a given location is ultimately based on the amount of climatic data available and the index's capacity to identify spatial and temporal fluctuations during drought events. Al-Timimi and Al-Jiboori (2013) analyzed drought characteristics at 39 meteorological stations over 30 years. The SPI analysis revealed that 1983, 1989, 1999, 2000, and 2008 were the most affected years. The severity of drought indices increased from normal to moderately severe, with 2008 being the worst year, with 30% of the area under extreme drought, 36% under severe drought, 22% under moderate drought, and 12% near normal [19]. Agha and Şarlak utilized SPI to analyze drought characteristics of ten meteorological stations from 1980 to 2011. Results showed maximum drought severity during 2007-2011, with the highest value in the north region of Iraq for SPI-9 and SPI-12. while 1999, 2008, and 2009 years were the worst drought years in Iraq [20]. Alwan et al. compared nine drought indices (RDI, Normal SPI, Gamma SPI, Log SPI, CZI, MCZI, RAI, PN, and DI) from 1988 to 2017, using seasonal and annual time scales. The Pearson correlation coefficient showed a maximum correlation between RDI, Gamma SPI, and Log SPI at all stations. These indices have similar drought classes and frequencies but have minimal differences between wet classes and goods for predicting and monitoring drought in the study area [21]. Agha conducted a study in the Nineveh region using the Chinese Z index (CZI). Historical data from 1981 to 2018 was used for Mosul, Sinjar, and Tal Afar stations. The highest drought intensity was experienced in March, with an average probability of moderate drought ranging from 0-0.31 [22]. The current research work aims to analyze the performance and application of three rainfall-based drought indices (SPI, CZI, and MCZI) to monitor and analyze the meteorological drought in selected stations in Iraq.

2.STUDY AREA

Iraq lies in the southwestern part of Asia within the longitudes (38°45′ to 48°40′) east and the latitudes (29°05′ to 37°20′) north. It shares borders with Turkey to the north, Iran to the east, Kuwait and Saudi Arabia to the south, and Saudi Arabia, Syria, and Jordan to the west. Its area is about 438,317 Km^2 [23]. Most geographers divide the geographical features of Iraq into four major regions: the western and southwestern desert regions; the highlands between the upper Tigris and the Euphrates; the mountainous heights in the north and northeast; and the sedimentary plain along the Tigris and Euphrates rivers, as shown in Fig. 1 (a) [24]. Annual rainfall varies from region to region; it usually decreases in the central and southwestern regions, where annual rainfall depth declines to less than 100 mm, then gradually increases headed towards the northeastern region, especially in the mountainous regions, to reach above 1000 mm [25], see Fig. 1 (b).

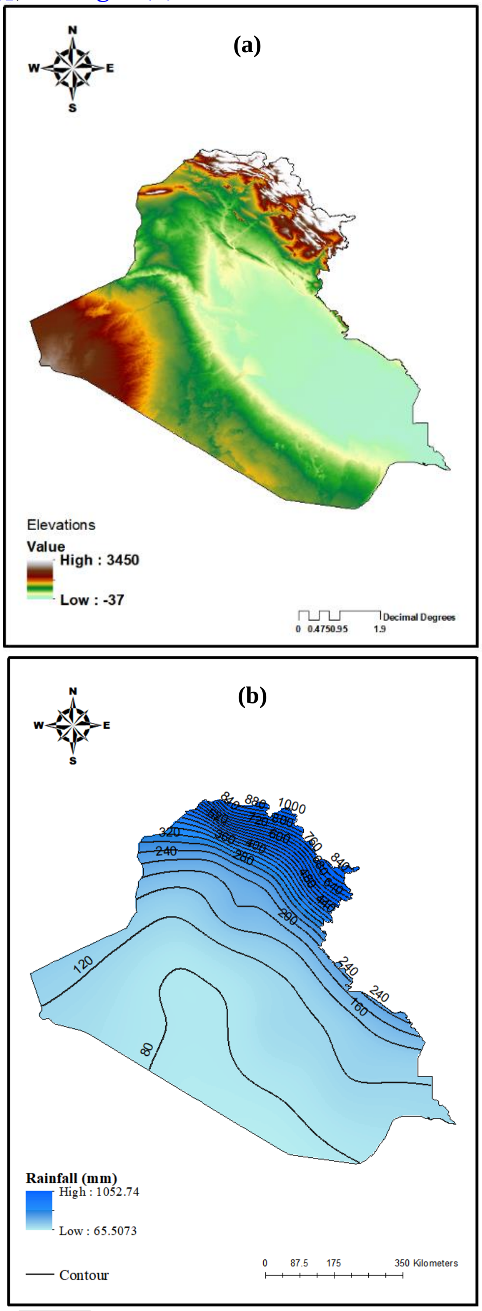


Fig. 1 The Study Area with the Spatial Distribution of Selected Meteorological Stations, (a) a Geographical Topography Map, and (b) an Annual Precipitation Mean Map.

The current work compares the performance of three meteorological drought indices with multiple time scales in various climatic regions of selected stations in Iraq according to Köppen climate classification in order to support effective drought monitoring in Iraq. In order to simplify the display of the results, only five stations have been used, which are Dukan, Kirkuk, Baiji, Rutba, and Basra (Fig. 2 and Fig. 3). These indices are the Standardized Precipitation Index (SPI), the China-Z Index (CZI), and the Modified CZI (MCZI). The metrological stations are scattered all over Iraq, and the list of the stations and their data statistics are given in Table 1.

Table 1 Selected Meteorological Stations and their Rainfall Data Statistics for the Period 1980–2021.

Station	Altitude (Meter)	latitude (Degree)	longitude (Degree)	Annual rainfall(mm) Min.	Max.	Mean	S. D
Dukan	490	35.95	44.95	232	953	599	178
Kirkuk	331	35.47	44.35	78	485	288	98
Baiji	116	34.90	43.53	72	397	198	79
Rutba	615	33.02	40.32	20	264	109	54
Basra	2	30.28	47.05	31	239	106	44

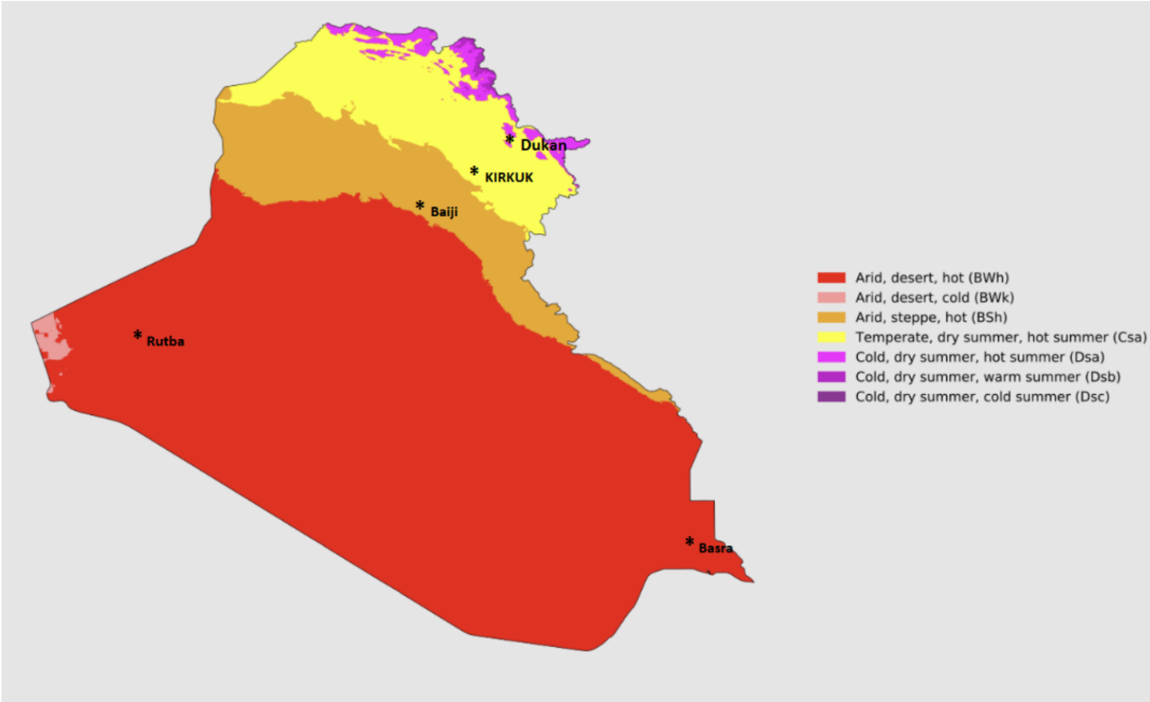


Fig. 2 Köppen-Geiger Climatic Map (1980–2016) [26].

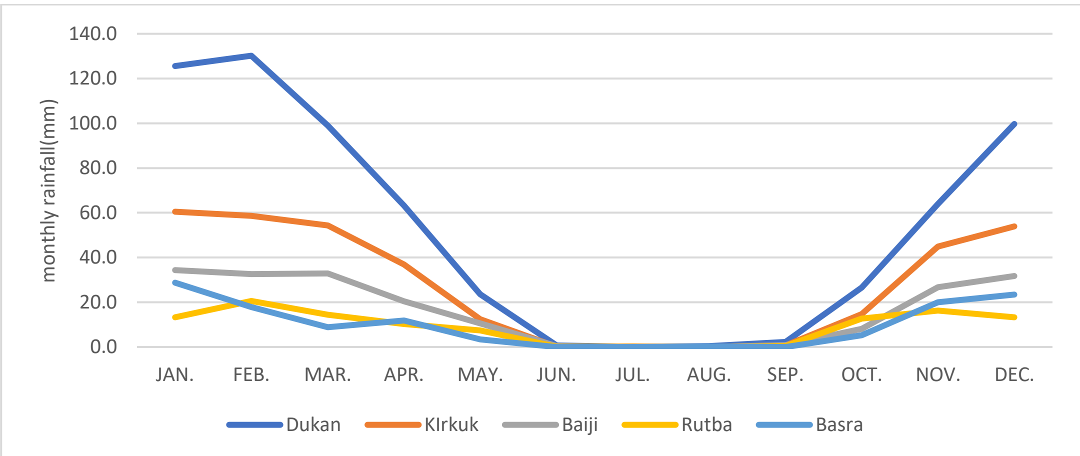


Fig. 3 Mean Monthly Precipitation at the Considered Stations for the Period 1980–2021.

The majority of the rainfall in Iraq lasts from October to the end of May. The monthly rainfall data for the five selected stations were collected from the Department of Meteorology and Seismic Monitoring in Iraq for the period of January 1980 to December 2021. In order to fill in missing data at these stations, the arithmetic average method and normal ratio method equations were used in conjunction with the data of the geographically nearest station.

3.THEORETICAL BACKGROUND

3.1.Standardized Precipitation Index (SPI)

McKee et al. [18] defined the Standardized Precipitation Index (SPI) as follows:

$$SpI = \frac{(p - \bar{p})}{\sigma_p} \quad \textbf{(1)}$$

Where p is the observed precipitation, $\bar{p}$ is the mean of the precipitation record, and σ_P is the standard deviation of the same precipitation record. It computes the standard deviation of precipitation data from a probability distribution function. Before being transformed into a normal distribution, raw precipitation data is often fitted to a Gamma or Pearson Type III distribution. The SPI values show deviations from the long-term mean that the observed anomaly deviates from the long-term mean [27]. Ideally, at least 20–30 years of monthly values are required, with 50–60 years (or more) being optimum and preferred with no missing values [28]. The SPI can be computed for periods ranging from 1 month to 72 months. According to statistics, the optimum practical range of its use is 1–24 months. When the time scale is extended to 12, 24, and 48 months, it responds more slowly to changes in precipitation, with fewer but longer SPI negative and positive periods [18]. On a relatively short timeline, soil moisture conditions respond to precipitation anomalies. The longer-term precipitation anomalies are reflected in groundwater, streamflow, and reservoir storage. For example, for meteorological drought analysis, a 1- to 2-month time scale SPI may be appropriate; a 1- to 6-month time scale for agricultural drought analysis; and a 6- to 12-month time scale or greater for hydrological drought analysis and applications [29]. The World Meteorological Organization (WMO) at 2009 suggested SPI as the primary meteorological drought indices that nations should use to monitor and track drought conditions and gave guidelines for nations attempting to develop a level of drought early warning by recognizing SPI as an index for general usage [30]. Positive SPI values indicate higher than median precipitation, while negative values indicate less than median precipitation [31]. Because the SPI is normalized, wetter and drier climates may be represented in the same way; consequently, wet periods can also be tracked using the SPI [32]. A drought event occurs at any time the SPI is continuously negative and reaches an intensity of -1.0 or less. The event ends when the SPI becomes positive [33].

3.2.China-Z index (CZI) and Modified CZI (MCZI)

The National Climate Centre of China developed the CZI as an alternative to the SPI in the early 1990s [34]. It's based on the Wilson–Hilferty cube-root transformation, it's superior to the SPI because of its simplicity, which makes the calculation much easier for the user. Drought periods may be identified and monitored using a statistical Z-score. The CZI is calculated as follows [35]:

$$Z_{ij} = \frac{6}{C_{si}}\left(\frac{C_{si}}{2}\varphi_{ij} + 1\right)^{1/3} - \frac{6}{C_{si}} + \frac{C_{si}}{6} \quad \textbf{(2)}$$

Where z_{ij} denotes the CZI, i is the time scale of interest, which might be 1, 2, 3,... 72 months, and j denotes the current month. The parameter i is not utilized in the NCC's CZI because only Z values for a 1-month time scale are computed.

$$C_{si} = \frac{\sum_{j=1}^{n}\left(x_{ij} - \bar{x}_i\right)^3}{n^*\sigma_i^3} \quad \textbf{(3)}$$

C_{si} is coefficient of skewness, n is total number of months in the record, φ_{ij} is standardized variate, also called the Z-Score, and x_{ij} is total precipitation of j month for the period i .

$$\varphi_{ij} = \frac{x_{ij} - \bar{x}_i}{\sigma_i}, \quad \textbf{(4)}$$

Both CZI and SPI are utilizing precipitation to identify wet and dry periods, but CZI assumes that precipitation follows a Pearson type III distribution. It employs monthly time increments ranging from 1 to 72 months, allowing it to detect droughts of varying lengths [36]. However, this index can analyze rainfall records even if they contain missing data [37]. This index's drawback is that the Z-score parameters do not follow the gamma or Pearson type III distributions. It was also noticed that the shorter time scale may weaken the index's performance when compared to the SPI. In order to calculate the Modified CZI (MCZI), the median of precipitation (Med) is utilized instead of the mean of precipitation as in the case of the CZI [17].

Table 2 Categories of the Drought Indices Considered in the Study [18].

Categories	Drought severity
Extreme wet	>2
Severe wet	1.5 to 2
Moderate wet	0.99 to 1.5
Normal	0.99 to -0.99
Moderate dry	-0.99 to -1.5
Severe dry	-1.5 to -2
Extreme dry	<-2

3.3.Theory of Runs

The 'run theory' proposed by Yevjevich (1967) was used to identify drought components and investigate their statistical properties. A drought event is defined as a consecutive sequence of months with drought indices values (X_t) less than a chosen threshold (X_o). It is characterized by the following components: drought initiation time (T_s), drought termination time (T_e), drought duration (D), drought severity (S), and drought intensity (I). Drought initiation time (T_s) is the onset month of a drought event; drought termination time

(T_e) is the date when the water shortage becomes sufficiently small; drought duration (D) is the time period between the initiation and termination of a drought; drought severity (S) is obtained by the cumulative deficiency of the drought parameter below the critical level; and drought intensity (I) is calculated as the ratio of the drought deficit value to the drought duration.

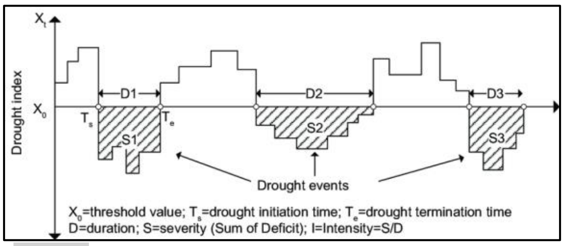


Fig. 4 Drought Characteristics Identification Using the 'Run Theory' [38].

4.RESULTS AND DISCUSSION

In the scope of this study, SPI, CZI, and MCZI were applied for five different time scales (1-month, 3-month, 6-month, 9-month, and 12-month) to the rainfall data of five meteorological stations scattered all over Iraq, and the performance of the indices was evaluated. The three indices showed high correlation among themselves, especially for the same timescale. Besides, there is a greater correlation with the creation of the time scale. It was shown that the values of the three indices were more convergent for time scales of 9 and 12 months, where correlations among the indices were greater than 0.85 in all stations (Fig. 5). Through Fig. 5, it is found that the correlation between the indices rises to more than 0.98 at the 9-month and 12-month timescales. The highest correlation values are for Dukan, but the correlation gradually decreases with the decrease in the annual rainfall rate for the considered stations. The indices showed high convergent frequencies of drought and wet categories in stations with high rainfall rates, in the mountains and semi-mountain areas, as in both Dukan and Kirkuk. Then their performances deviate from each other for the stations with a lower rainfall rate, such as Baiji, Rutba, and Basra. In Basra station, where the drought set in in November 2021, the values of each CZI and MCZI were -4.4 and -4.1, respectively, while the SPI value was -3.1, and the same applies to the wetness values: the SPI showed an extreme wet period in February 1980, with a severity of 4.4, while the other two indices, CZI and MCZI, showed only 2.5 and 2.6 severity, respectively. From Fig. 6, it is found that the SPI with a 1-month time scale shows a higher frequency of dry months, while the MCZI shows a higher frequency of wet months. By increasing the time scale to 3, 6, 9, and 12 months, it is found that the two indices show terms of dryness and wetness in a convergent manner, as the figure shows the median approaching the average (zero). The time-scale 1-month describes the studied period as a normal to wet period, while the time-scale 3-month describes dryness more severely, then the time-scale 6-month and the time-scale 9-month describe the studied time period with the greatest drought frequencies, and the time-scale 12-month is close to the time-scale 9 but with an estimate of dryness less than the time-scale 9-month.

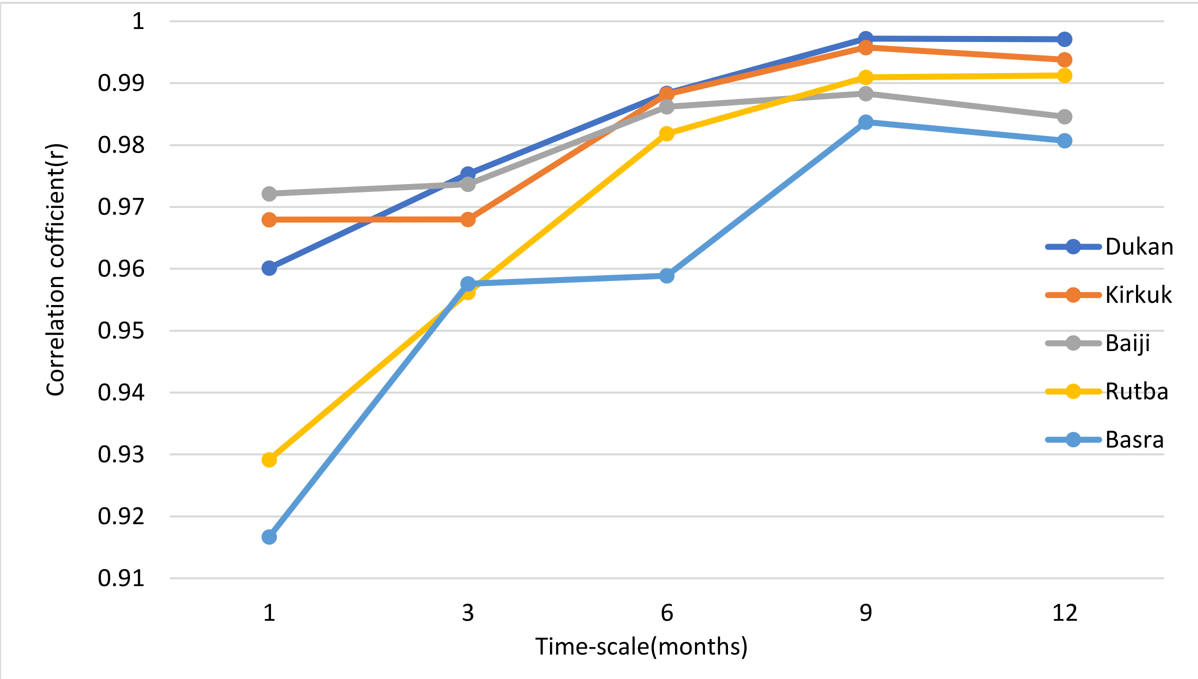


Fig. 5 Average Correlation Coefficient Values for the Three Indices on Different Time Scales.

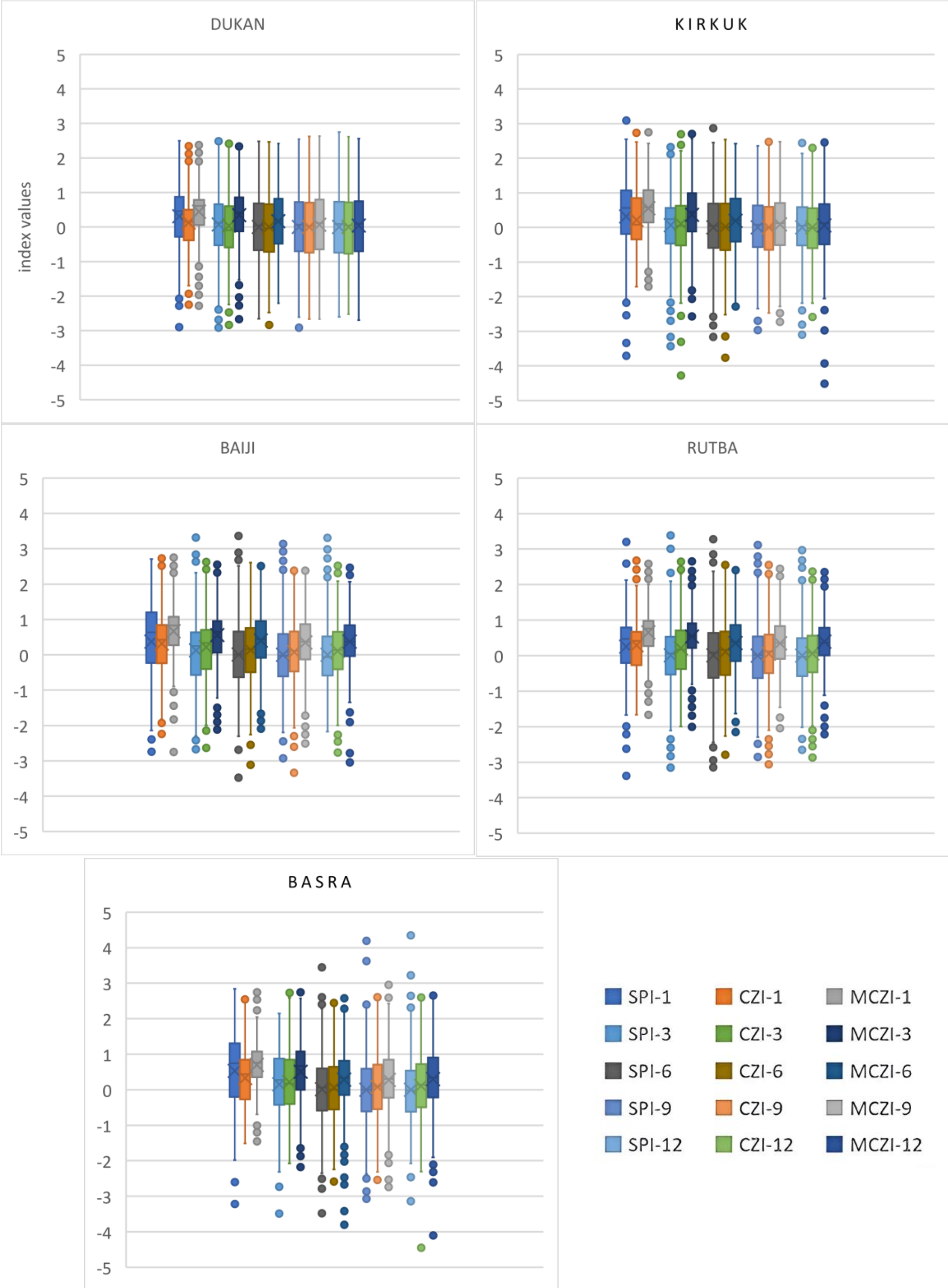


Fig. 6 Dry and Wet Months with Different Timescales Through the Period 1980–2021.

It's also noticed through the box plots that in the southern stations, the indices values are more divided from the normal value in both cases of drought and witness, while the values in the northern stations are more homogeneous. It is found that the SPI always shows signs of drought earlier, this is in agreement with the results of previous works [39], with higher values and longer periods than the other two indices, especially at the 1-month time scale. Accumulated SPI totals with negative values are used as a measure of drought severity. Table 3 shows that the number of drought events in the northern stations was lower, but the durations of those events were longer than in the southern stations. Comparing the northern and southern stations with the same index and time scale, the northern stations with a higher rainfall rate have more dry months than those of the southern stations that have a lower rainfall rate, this is in agreement with the results of previous works [40]. Besides that, it is believed that the droughts in the northern stations are more severe and occur with greater frequency than those in the southern stations. It's noticed from Table 3 that the indices gave close results at the northern stations, while the results deviate from each other as we head towards the south. The period 2007–2010 was the most severe drought event during the study period in all stations, as those stations recorded the highest drought severity. This is in agreement with the results of previous work done in Iraq [41-43]. 2021 was one of the driest years during the studied period, this is in agreement with the results of [44], as most of the months during the year were within the classification of extreme drought. The percentage of rainfall in 2021 was at the stations in Kirkuk, Baiji, and Basra, in proportions of 23%, 36%, and 27% of the average rainfall of the station, respectively. The worst drought event to ever affect Kirkuk Station occurred in 2007, this is in agreement with [19], with a cumulative severity of 25.

The highest drought value for all the indices appeared in Baiji station, where its value was -3.4 for the SPI index, while the maximum values for the CZI and MCZI were -2.6 and -2.5, respectively, in the same station. However, Kirkuk station presents the longest drought period (26 dry months for SPI and CZI, and 25 dry months for MCZI). The number of dry months for all stations increases with the increase in the time scale for the SPI (Fig. 7), as it is the lowest in the 1-month timescale and reaches the maximum in the 12-month timescale. The opposite occurs in the other two indices, where the number of dry months decreases with an increase in the time scale. The SPI results showed the most dry months, while the MCZI showed the least dry months.
To show the results more accurately, we mostly rely on the 12-month time-scale, as it is the strongest of the two indices (SPI and CZI); this is in agreement with the results of previous works [45, 46].

Table 3 Drought Characteristics with SPI, CZI, and MCZI at a 12-Month Time Scale from 1980 to 2021 for the Considered Stations.

Stations	Frequency of drought events	Total drought months	Sum. of drought severity	Maximum indices values	Set-on of maximum drought events	Duration of maximum Drought event (month)	Severity of maximum Drought
SPI-12							
Dukan	10	92	50	2.6	1999-1	24	12
Kirkuk	11	84	54	3.1	2007-10	26	25
Baiji	12	81	35	2.2	1998-12	24	16
Rutba	14	74	41	2.7	2017-1	16	11
Basra	14	76	44	3.1	2009-1	11	9
CZI-12							
Dukan	10	92	43	2.6	2008-2	22	13
Kirkuk	11	83	45	2.5	2007-10	26	20
Baiji	16	55	32	2.6	2008-5	5	6
Rutba	19	62	49	2.5	2017-2	6	7
Basra	17	75	42	2.3	2009-1	11	9
MCZI-12							
Dukan	10	92	41	2.5	2008-2	22	12
Kirkuk	8	71	45	2.4	2007-11	25	21
Baiji	8	20	10	2.5	2012-4	7	3
Rutba	13	28	13	2.4	2002-2	8	6
Basra	12	54	36	2.2	2009-1	9	8

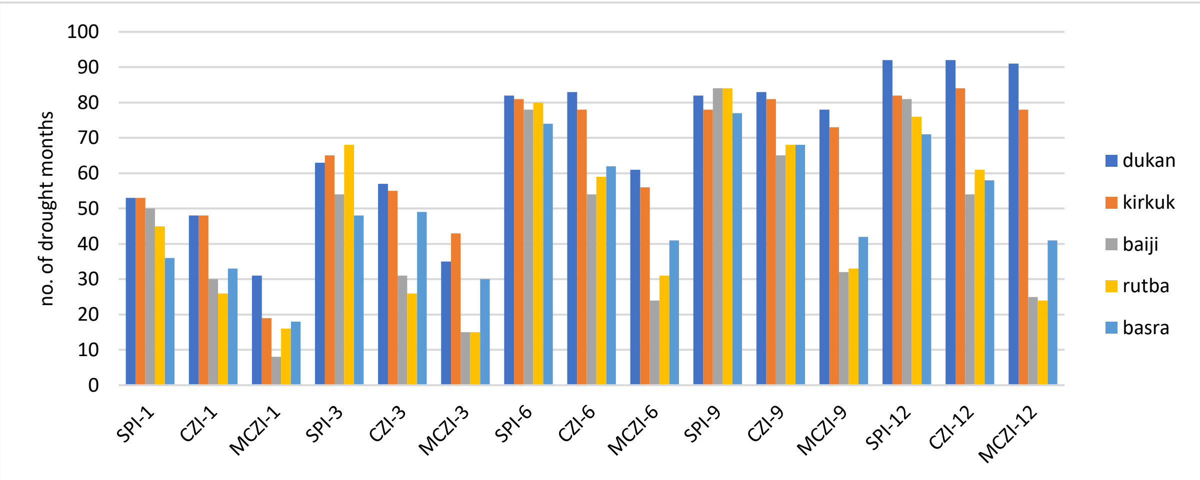
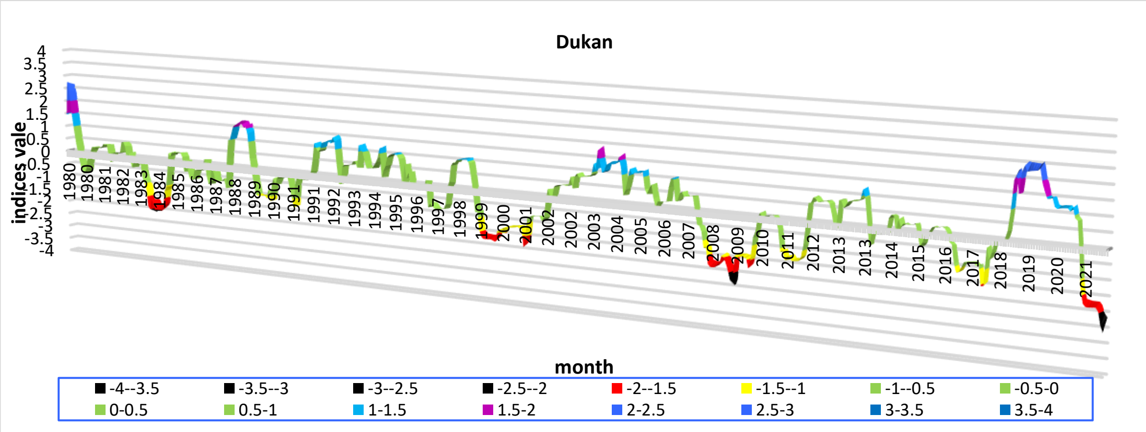
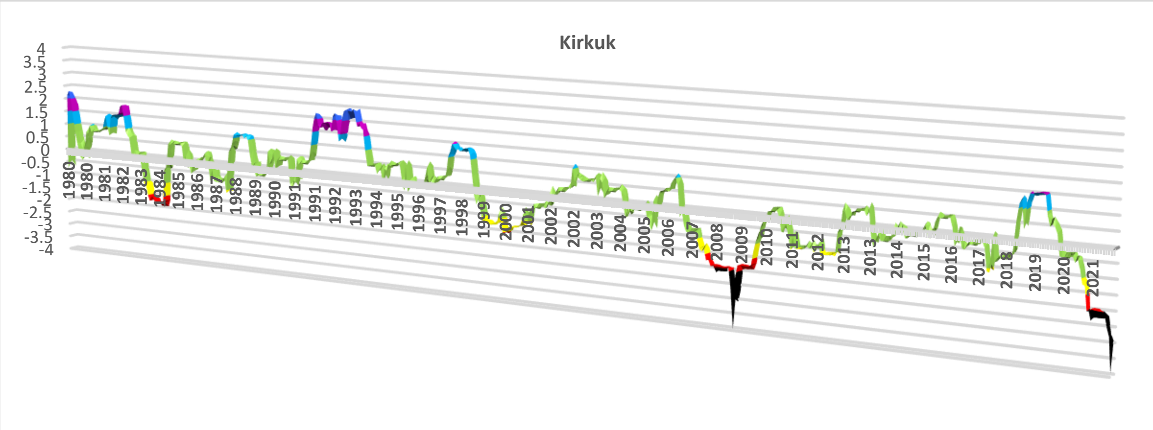
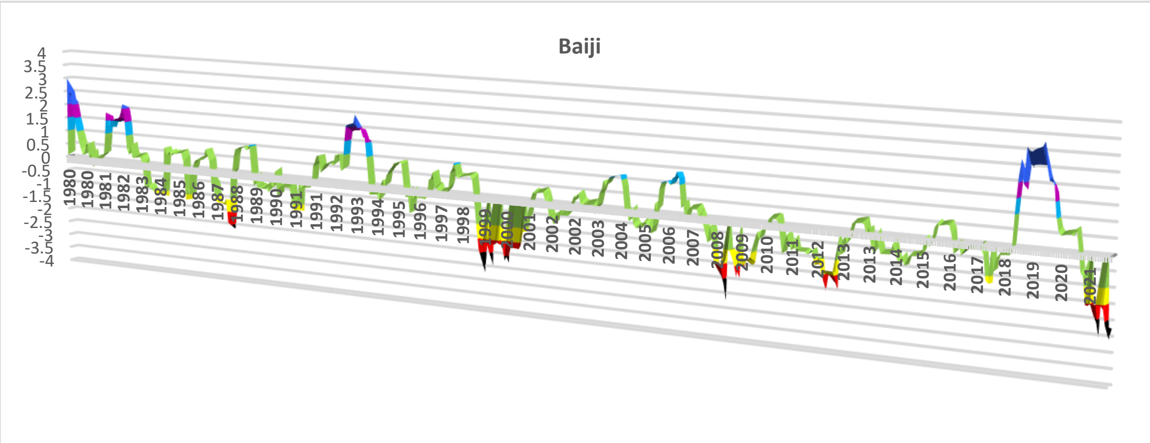
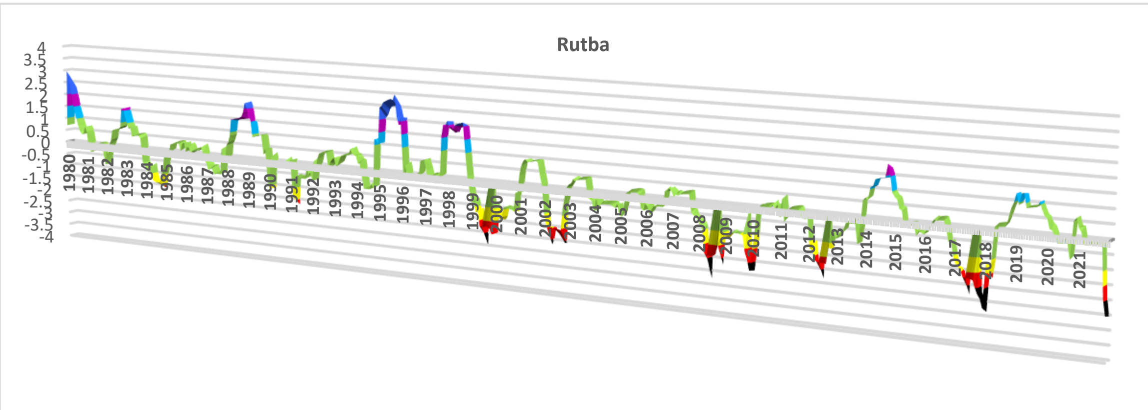


Fig. 7 The Number of Drought Months for Each Time Scale Considered in the Study.


Dukan
indices vale
month
-4--3.5
-3.5--3
-3--2.5
-2.5--2
-2--1.5
-1.5--1
-1--0.5
-0.5-0
0-0.5
0.5-1
1-1.5
1.5-2
2-2.5
2.5-3
3-3.5
3.5-4


Kirkuk


Baiji


Rutba

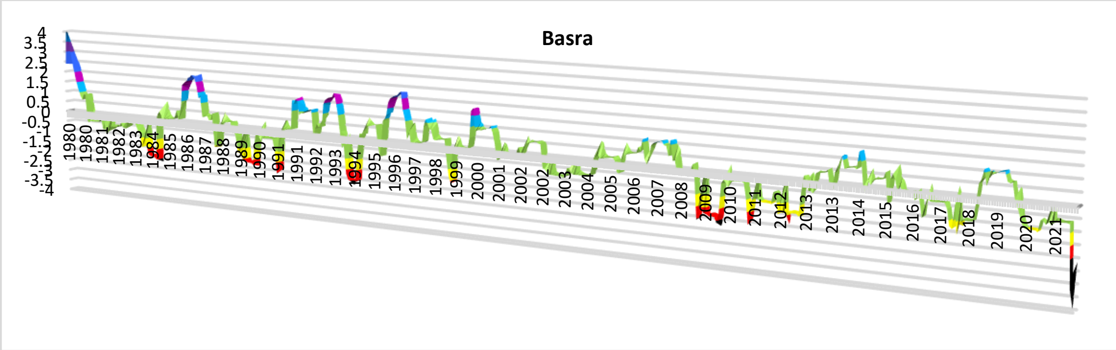


Fig. 8 Drought and Wetness Frequency in SPI-12 and CZI-12 from 1980 to 2021 for the Considered Stations.

Most of the indices values are in the normal and moderate drought zones. Few months fall within the severely and extremely dry zones. This means that Iraq's climate is normal to moderate; this result is also stated in previous research work [47]. From Table 4, it is clear that 1999, 2008, and 2021 were the worst drought years in Iraq. During the study period, Kirkuk station was the most affected by the drought because it got only 23% of the annual average rainfall in 2021. While 1980, 1993, 1995, and 2019 were the most wet years, the Baiji station recorded the highest wetness in 1995, when the rainfall reached 212% of the annual mean.

Table 4 The Most Severe Wet and Dry Years in the Stations Through the Study Period (1980–2021) for SPI-12.

	Most Wet Year		Most Drought Year	
Stations	**Year**	**Sum of Index Value**	**Year**	**Sum of Index Value**
Dukan	2019	26	2008	-19
Kirkuk	1993	23	2021	-26
Baiji	2019	34	2021	-17
Rutba	1995	30	1999	-17
Basra	1980	26	2008	-19

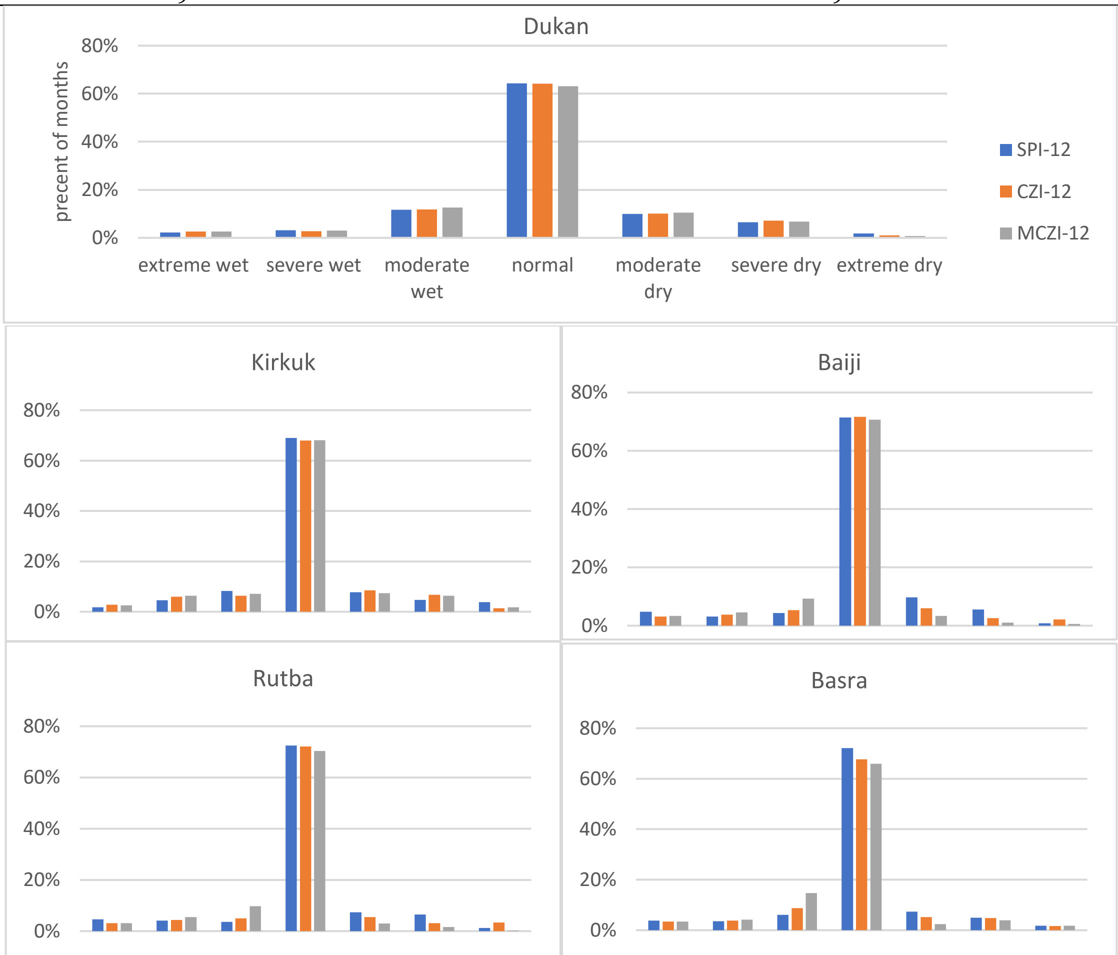
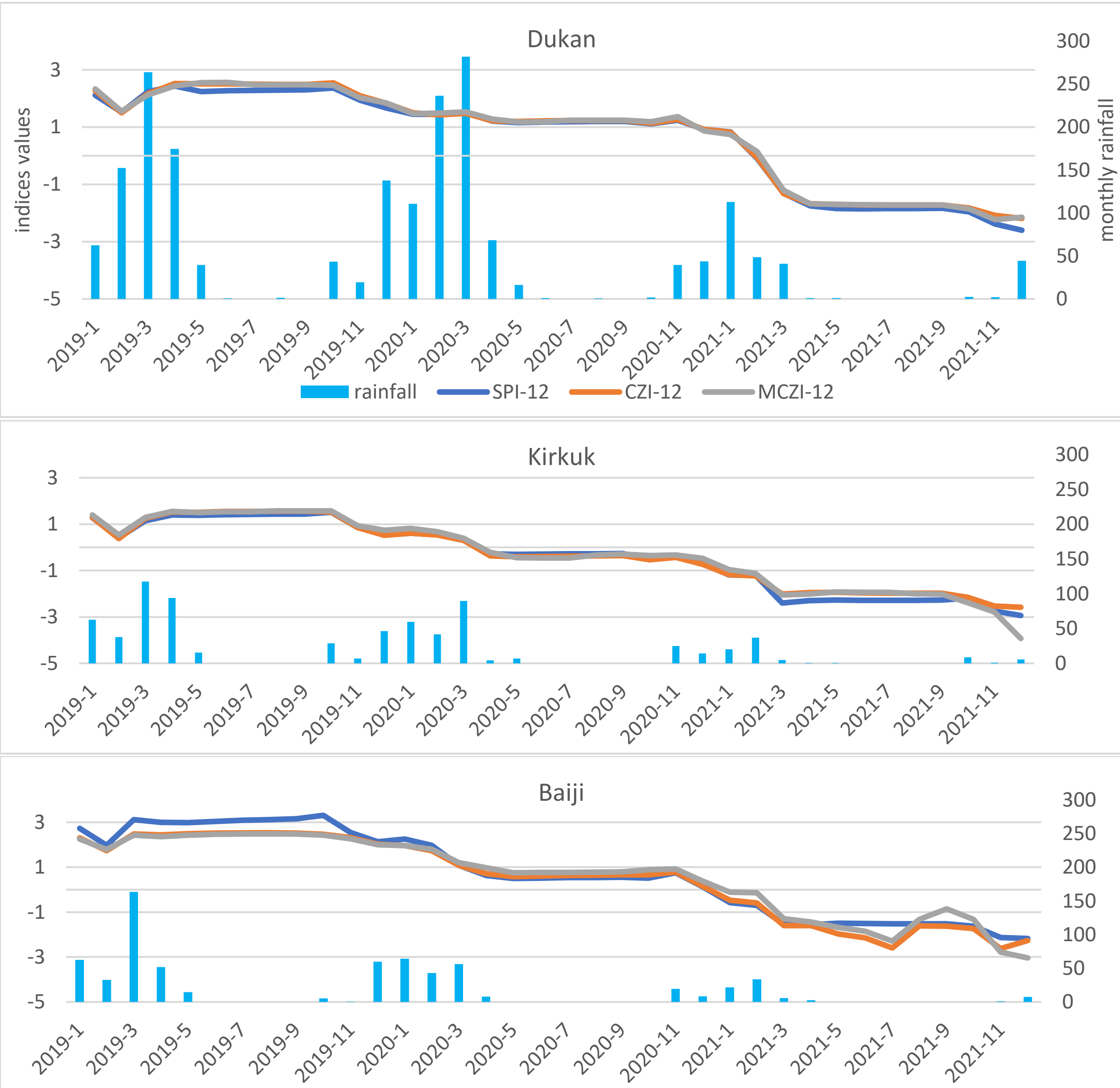


Fig. 9 Drought and Wetness Classes for Each Index with a 12-Month Time Scale for the Considered Stations.

Fig. 9 revealed that the most of the indices values are classified within the normal class at all stations, and the stations of the northern region of Iraq are more exposed to drought events than those of other regions, which have a lower rate of rainfall, as the percentage of dry months in Dukan station, for the SPI-12, reached 19%, while in Kirkuk and Baiji it were 17%, and in Rutba and Basra it were 15%. The CZI index results have a high correlation comparing to the other two indices results. The greatest correlation was at the northern station, Dukan, and it was also weakened by gradually heading towards the south. However, this index is better than the MCZI in drought analysis in the southern region and has a high correlation value with the SPI. To illustrate the performance of the three indices, the years 2019, 2020, and 2021 were taken as examples, where 2019 was a wet year, 2020 was a transitional year, and 2021 was a very dry year in Iraq, as shown in Fig. 10. It is interesting to see how the matching weakens between the indices values as we head south; MCZI gives values that are far from the other two indices and deviates far from the median value, while CZI remains more compatible with the SPI and MCZI. Even though Eq. (2) used the median instead of the mean value to minimize the performance gap between SPI and CZI, this was not shown in this study. As the performance of the CZI index has lost its high correlation with the SPI index and the MCZI, this result is also stated in previous research [35, 48]. Table 5 shows the correlation value between the three indices values and the monthly rainfall rate for the 9-month and 12-month timescales. The correlation value between the rainfall data and the CZI-9 index is higher than that with the SPI-9. While SPI-12 results were more correlated with rainfall data than the other indices.



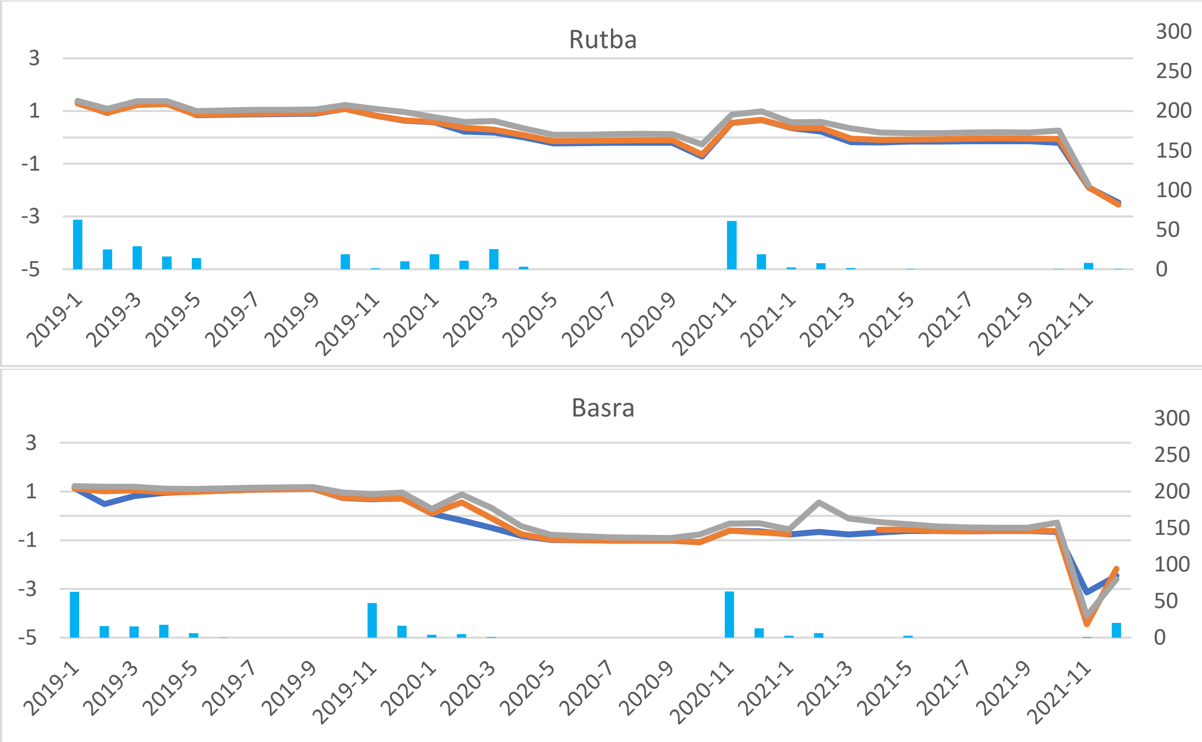


Fig. 10 Values of the Drought Indices at a 12-Month Time Scale for the Period January 2019 to September 2021 for the Considered Stations.

Table 5 The Correlation Coefficient Among Rainfall Data and Drought Indices for the 9-Month and 12-Month Timescales for the Considered Stations.

Indices \ Stations	Dukan	Kirkuk	Rutba	Baiji	Basra
SPI-9	0.71	0.75	0.81	0.84	0.69
CZI-9	0.72	0.76	0.77	0.81	0.71
MCZI-9	0.69	0.74	0.76	0.79	0.64
SPI-12	0.99	0.98	0.98	0.96	0.98
CZI-12	0.99	0.99	0.93	0.92	0.95
MCZI-12	0.99	0.97	0.91	0.92	0.91

It is clear that CZI's results were the most similar to SPI's, especially on a long-time scale. It can be considered that these two indices are better for analyzing both drought and wetness in Iraq. This means that the CZI may be a better index for interpreting the characteristics of the meteorological drought in Iraq on a 9-month time scale if we take into consideration that the SPI does not accept missing data and requires rainfall data for a long period. It could be an alternative index for SPI for analyzing the meteorological drought in Iraq in general.

5.CONCLUSION

In order to study drought characteristics in Iraq in a more accurate way, three drought indices (SPI, CZI, and MCZI) were used on five-time scales (1, 3, 6, 9, and 12) for different climates in Iraq, depending on Köppen climate classification and taking one station from each calamitic. The stations were Dukan, Kirkuk, Baiji, Rutba, and Basra. The concluding remarks are given below:

- A very high Pearson correlation coefficient (r) among the indices, especially for the same time scale. Besides, their value increases with the lengthening of the time scale.
- The performance of these indices were more convergent for the time scales of 9 months and 12 months.
- The indices gave close results at the northern stations, while the results diverged as we headed towards the south.
- The SPI indicated drought events earlier and more severely than the other two indices, while the MCZI showed wetness events earlier than the other two indices.
- Most of the indices values ranged within the normal and moderate drought zones.
- Drought values were more severe on the 6-month and 9-month time scales.
- The CZI index is better than the MCZI in drought analysis and has a higher correlation value with the SPI. This index describes drought better than the MCZI in the southern region of Iraq.
- CZI could be an alternative index for SPI for analyzing the meteorological drought in the study area.

- The number of dry months for all stations increases with the increase in the time scale.
- The northern stations contain the fewest dry months compared to the southern stations for the same index over the same time scale but suffer from more severe drought events, although the frequency of drought in the northern stations is higher than that in the southern stations.
- Kirkuk station presents the longest drought period.
- The highest drought value for all the indices appeared in Baiji station.
- The years 1980, 1993, 1995, and 2019 were the wettest years during the studied period.
- The years 1999, 2008, and 2021 were the driest years during the study period at all stations.
- SPI, CZI, and MCZI are not the only drought indices that may be employed. Also, more research on local climatic conditions with meteorological data is needed to reduce uncertainty in drought assessment and offer a better tool for managing and planning water resources in Iraq.

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