ORIGINAL ARTICLE

Assessment of Drought Conditions Over Different Climate Zones of Kazakhstan Using Standardised Precipitation Evapotranspiration Index

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Abstract

The present research was carried out to understand the long-term changes in drought conditions over major climate regions of Kazakhstan using the temperature-sensitive Standardised Precipitation Evapotranspiration Index (SPEI). The inter-annual and intra-annual drought events were studied by computing SPEI at resolute time scales such as SPEI 1, SPEI 3 and SPEI 12. The non-parametric statistical metrics including the Mann–Kendall test and Sen's slope estimator were used to find the direction and magnitude of trends shown by the index. The results of the study revealed a significant drying tendency of the arid and semi-arid climate zones. An insignificant wetting tendency was observed for the humid and sub-humid climate zones of the country. The analysis of SPEI 3 showed that the summer and autumn seasons made a significant contribution to the dry periods in the semi-arid climate zone while the spring season aided in generating a similar downward trend in the arid climate zone. April, August and September were recorded as the months with the highest occurrence probability of total droughts in all the climate divisions of Kazakhstan. Until the point of probable meteorological change in 1994; the central longitudinal position occupied by the highest possibility occurrence areas for overall droughts showed a westerly and north-easterly shift during the subsequent period. The drought index also reflected an increased occurrence probability of all types of droughts with an obvious shift in the intensive drought centers during the studied time slices. However, the range of occurrence probability shrank with the increasing severity of droughts.

Keywords Drought · Kazakhstan · SPEI · Variability

1 Introduction

Drought is a natural event of an unknown magnitude that occurs as a result of a combination of several factors primarily including the lack of precipitation (Wilhite and Glantz

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1985; Törnros and Menzel 2014; Wilhite 2014; Wang et al. 2016; Haied et al. 2017; Chen et al. 2018; Moghimi and Zarei 2019; An et al. 2020). It is an insidious hazard characterised by non-structural impacts with a large spatial extent (Gillette 1950; Wilhite 2014). It has the potential to influence different sectors of the economy particularly agriculture, water resources, affect ecosystem functioning and even induce political instability in certain areas (Song et al. 2003; Zou et al. 2005; Ma and Fu 2006; Xin et al. 2006; Lu et al. 2011; Wang et al. 2011; Wang et al. 2012; Yan et al. 2011; Liu and Jiang 2014; Azadi et al. 2015; Mokarram et al. 2015; Zarie 2018). The present climate change has exacerbated the occurrence frequency and intensity of hydrological and meteorological events like floods and droughts (Yu et al. 2014; Li et al. 2018; Guo et al. 2018; Chen et al. 2018) with a greater potential of a further increase in the future (IPCC 2014).

The existence of many conflicting definitions and their associated inherent weaknesses make drought investigation

a difficult task (Glantz and Katz 1977). Lack of a universally accepted definition adds confusion to whether a drought has set in or not and if yes, how severe or extreme is it and when has the event terminated (Wilhite et al. 2014). As there exists a lot of disagreement about the concept of drought, there arises a strong need to define a drought (Histal and Talleksen 2000). Wilhite and Glantz (1985) analysed 150 definitions of drought and were successful in classifying them into four different types viz. meteorological drought, hydrological drought, agricultural drought and socioeconomic drought. American Meteorological Society (AMS) also reports these four drought types. However, Dai (2011) reported only three types of drought with no mention of socioeconomic drought. Experts from time to time have been engaged in working out possible metrics to understand and characterise droughts in terms of their intensity, severity, duration and spatial extent (Şen 2015; Guo et al. 2018; Sharafati et al. 2019; Hosseini et al. 2021). Over the years, several indices were developed to monitor droughts to provide some valuable suggestions regarding mitigation and early warning of such events. The drought indices range from simple ones like precipitation percentiles and percentage of normal precipitation to complex ones like Palmer Drought Severity Index—PDSI (Palmer 1965). Some of the indices are based on precipitation only like Standardized Precipitation Index—SPI (McKee et al. 1993) and Actual Precipitation Index—API (Şen and Almazroui 2021) while some others like Standardized Precipitation Evapotranspiration Index—SPEI (Vicente-Serrano et al. 2010) on temperature, precipitation and other derived variables. Some of the drought indices such as Standardized Runoff Index (Shukla and Wood 2008) and Streamflow Drought Index (Nalbantis and Tsakiris 2009) require hydrological observations for their applicability while some others such as Vegetation Condition Index (Kogan 1990) depend entirely on remote sensing data. Looking at the availability of the data and the purpose of the current study SPEI was preferred over others. SPEI is a multi-scale temperature-sensitive method with easy spatial comparability (Guo et al. 2018) and can prove beneficial in capturing the effect of the current warming trend on droughts (Vicente-Serrano et al. 2010). PDSI was not used because of some of its inherent limitations such as fixed timescale (Keyantash and Dracup, 2002), computational complexity (Guttmann, 1998), dependency on data calibration (Alley 1984), difficulty in regional comparisons (Andreadis et al. 2005), etc. SPI was not applied because the index uses only precipitation as an input parameter (WMO 2012) and no soil water balance component could be calculated which forms an important constituent for characterisation of droughts of different time scales.

A plethora of studies exists in literature that has mainly focussed on the characterisation of droughts especially in the arid and semi-arid part of the world. Wang et al. (2016) analysed the concept of drought propagation and investigated different aspects of the propagation of droughts through several stages. Yang et al. (2016) reported rising drought frequency in the Haihe river basin of China from 1960 to 2010. Chen et al. (2018) analysed the spatiotemporal variations in drought conditions in Yangtze River basin of China. The results revealed complex variations reflected in the river basin over various timescales and the existence of a strong correlation between SPEI-3 and TVDI (Temperature Vegetation Dryness Index). Sarış and Altin (2020) determined the hydrological drought intensity in two river basins of Turkey for 43 years. Results of the analysis indicated that the frequency of droughts was highest during the months of October to December. Besides a strong negative trend was reported in the basins from the early 2000s. An et al. (2020) reported increased intensification of droughts as a result of steep temperature increases in Xinjiang province of China from 1960 to 2018. Hosseini et al. (2021) used the Drought Index (DI) of GPCC to analyse the dry and wet periods in Iran for a period of 68 years. The authors found a significant increase in drought occurrences in arid basins and a hike in the number of drought centers. Despite an arid, semi-arid territory, a small number of attempts have been made in Kazakhstan to study long-term changes in drought characteristics. Dubovyk et al. (2019) analysed the spatial component of droughts in Kazakhstan using remote sensing data during 2000–2016. Salnikov et al. (2016) assessed the impact of atmospheric drought variability on crop yield fluctuations in Kazakhstan, using Selyaninov Hydrothermal Coefficient (SHC). The study distinguished the major production areas based on the instability of crop yields and found soil moisture as a strong limiting factor for summer crop yield. The present study differs from the previous studies in the sense that it examines the dry spells at different time lags in the current scenario of changing climate and evaluates the spatial and temporal variability of different levels of droughts while considering different climate zones. The research would help in prioritising different spatial units according to their vulnerability to dry periods and would be highly beneficial to the competent authorities in framing relevant adaptation strategies for the concerned regions.

2 Geographical Setting

Kazakhstan is located in the heart of Eurasia extending from 40.56° N to 55.26° N latitudes and 46.45° E to 87.35° E longitudes (Fig. 1a). Mean elevation of the country is 387 m AMSL with the lowest (− 132 m) and highest (6995 m) points located in the Caspian lowlands and Tian-Shan mountains, respectively (CIA 2019). The territory reflects a continental type of climate suffering from extremes of temperature on different temporal scales (de Beurs and
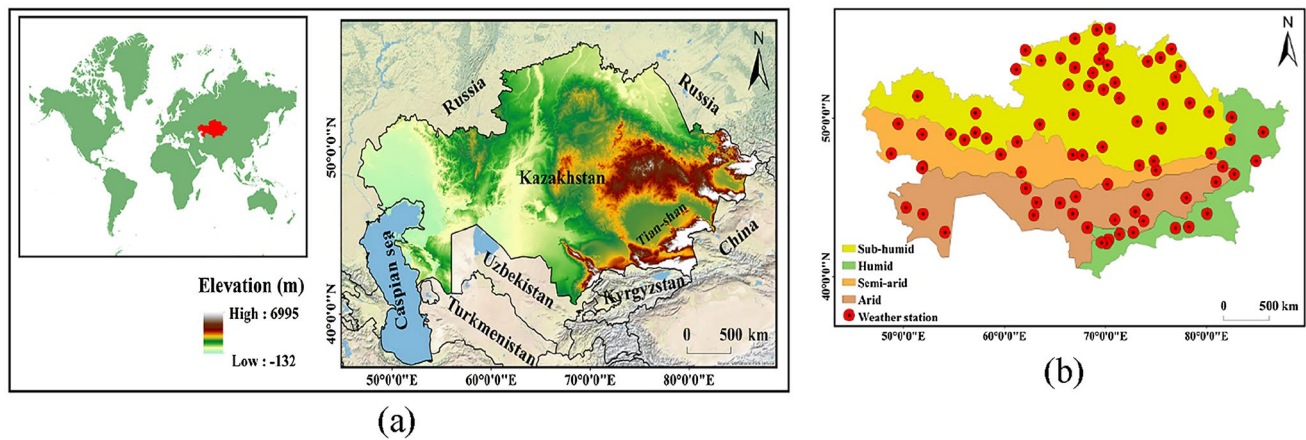
Fig. 1 Maps showing the **a** location of Kazakhstan and **b** distribution of meteorological stations in major climate regions

Henebry 2004; Salnikov et al. 2014). The country lacks a direct contact with an open sea that has a profound influence on its climate (Issanova and Abuduwaili 2017; Yapiyev et al. 2017). The climate of Kazakhstan is broadly divided into four types—sub-humid continental climate, cold arid climate, semi-arid climate and mountainous climate (Cherednichenko et al. 2021) (Fig. 1b). The average January temperature is— − 20 °C in north and − 5 °C in south while the average July temperature varies from 18 °C in north to 29 °C in south (Lydolph 1965; USAID 2017). The mean minimum temperature may reach upto − 40 °C in January in the northern sub-humid climate region of the country while the mean maximum temperature crosses 40 °C in the low-lying plains in the month of July (Salnikov et al. 2014). Precipitation is highly uneven both in amount and in concentration across the country. The country receives an annual precipitation of 200–400 mm in the sub-humid north (Klein et al. 2012) and 450 mm in some southern mountainous areas (de Beurs and Henebry 2004; Salnikov et al. 2014). The amount is much lower in the semi-arid and arid climate zones in the western and southwestern parts of the country that receive less than 100 mm annually (de Beurs and Henebry 2004; Issanova and Abuduwaili 2017; Dubovyk et al. 2019). However, eastern and southeastern mountainous areas and foothills receive the highest recorded precipitation of ≥ 1000 mm per year (Issanova and Abuduwaili 2017; Dubovyk et al. 2019). The westerlies play a dominant role in the climate of Kazakhstan (Bridgman and Oliver 2006; Chen et al. 2009). A north to south shift in the westerly winds cause precipitation over the region during the warmer and colder parts of the year by deriving moisture from North Atlantic and Mediterranean Sea, respectively (Bothe et al. 2011). The interaction of the Siberian High and the North Atlantic Oscillation (NAO) influences the cold season climate while the interaction between Azores High and Asian Low affects the warm season climate (Rogers and Loon 1979; Aizen et al.

2001; Meeker and Mayewski 2002; Issanova and Abuduwaili 2017). Precipitation is also promoted by the frequent southward invasion of the polar front or arctic front (Aizen et al. 2001).

The situation of the country makes it extremely vulnerable to physical fluctuations of the changing climate (Wiley NHDR 2008). The climate of Kazakhstan is characterised by the occurrence of frequent droughts (Salnikov et al. 2014) which along with increasing continentality (Lopez Fernandez et al. 2020) produce a profound impact on different components of socioeconomic and biophysical systems specifically agriculture and water resources (Gessner et al. 2012; Kariyeva et al. 2012; Sun et al. 2020). Water deficit is the most significant factor that limits plant growth in the region (Iijima et al. 2008). Since major cultivation is dependent on rainfall during the growing season, dry periods can reduce the agricultural output to a considerable degree (Fehér and Fieldsend 2019). Agricultural droughts have a disastrous impact on crop production and yield particularly in the northern steppe region that is considered as a significant granary of the entire Eurasian continent (Iijima et al. 2008; Dubovyk et al. 2019). Relatively small-scale droughts are a persistent phenomenon in southern parts of the country (World Bank 2006). The northern parts of the country are less vulnerable to droughts in comparison to their southern counterparts mostly due to more precipitation quantities received by the northern steppes in comparison to the arid and semi-arid south (Ta et al. 2018).

3 Materials and Methods

3.1 Data Source

Monthly temperature and precipitation data for the selected meteorological stations were retrieved from National Centers

for Environmental Information's (NCEI) online data portal accessible at https://www.ncdc.noaa.gov. Previous researchers (Russel et al. 2018; Farooq et al. 2021; Salehie et al. 2021) have used similar dataset for the desired variables in their respective studies. Assessments carried out by Russel et al. (2018) reported good to adequate data length, consistency and spatial coverage of mean temperature and precipitation in Kazakhstan. Farooq et al. (2021) agree with the same after proper infilling of the time series. The monthly observational time series at different stations were checked for any kind of non-climatic heterogeneity using Standard Normal Homogeneity Test (SNHT). Meteorological stations were selected from all the major defined climate and altitudinal divisions of the country (Fig. 1b). A detailed description of the selection of meteorological stations and imputation of missing data associated with the stations can be found in Farooq et al. (2021). A geographical description of the selected stations is provided in the supplementary material (Table S1).

3.2 Methodology

SPEI at various time lags was calculated for the selected meteorological stations spread across various climate zones of Kazakhstan. The procedure of SPEI calculation involves several steps (Yu et al. 2014; Yang et al. 2016; Shen et al. 2017). The initial requirement of calculating Potential Evapotranspiration (PET) for the index was ascertained by utilising Thornthwaite's equation (Thornthwaite 1948). After that, the climatic water balance was worked out for different months by taking the difference of monthly precipitation and Potential Evapotranspiration (PET) into consideration (Vicente-Serrano et al. 2010). The final index was generated by fitting a three-parameter log-logistic cumulative distribution function to the climatic water balance component obtained at various time scales (An et al. 2020). SPEI was classified into different drought categories as shown in Table 1. All the calculations were performed using "SPEI package" in R software (http://sac.csic.es/spei). Yang et al. (2016), Shen et al. (2017) and An et al. (2020) followed similar calculation procedure and categorisation of SPEI in their respective studies.

Table 1 Classification of SPEI values into different drought categories

| SPEI	Drought category
More than − 0.5	No drought
− 0.5 to – 1	Mild drought
− 1 to – 1.5	Moderate drought
− 1.5 to – 2	Severe drought
Less than − 2	Extreme drought

The trend analysis of various SPEI time series was carried out using Mann–Kendall (M–K) statistical test (Mann 1945; Kendall and Stuart 1976). As a non-parametric statistical metric, M–K test does not require the dataset to be normally distributed and can be applied to other non-normal distributions as well (Hess et al. 2001; Meals et al. 2011). In the case of non-normality, the test provides greater statistical power and is less sensitive towards extreme values and missing data gaps (Meals et al. 2011). Prior to the application of the test, the time series were checked for serial correlation that has the potential to reduce the reliability of the results obtained. Positive auto-correlation in the data sequence increases the possibility of a significant answer, even in the absence of a trend (Cox and Stuart 1955). The Sen's slope estimator (1968) was used to find the magnitude of trends. Like M–K test, the method was preferred due to its more robust nature towards outliers and superior performance for varied distributions (Hirsch et al. 1982).

4 Results and Discussion

4.1 Inter-annual and Seasonal Variability of Droughts

SPEI calculated at a time lag of 12 months (SPEI 12) was used to evaluate the long-term changes in drought conditions on an annual scale for the selected time period. Figure 2a shows the interannual variability of SPEI values for Kazakhstan from 1970 to 2017. The M–K statistic ($z = − 0.471$) calculated for the annual SPEI time series reported an insignificant tendency of the region towards a negative SPEI run. Lowest SPEI values were shown in the years 2008 and 2012 when the SPEI values dropped to a minimum value of − 1.182 and − 1.381, respectively. For the sub-humid climate region, the interannual variability of droughts showed a strong fluctuating nature for the studied time period as depicted by the SPEI 12 values. The SPEI reflected several negative runs from the beginning of the time period such as from 1974 to 1978, 1997 to 1999 and for 2008, 2010 and 2012 (Fig. 2b). The SPEI 12 values for the area were random, not propagating in a particular direction for the studied time period. The trend line drawn for the data series was also statistically insignificant. The humid climate zone showed similar interannual changes as were reported by the sub-humid climate zone. The climate region also showed strong fluctuating SPEI 12 values through the selected time frame. The negative values were noticed from the years 1973 to 1975, 1995 to 1997 and 2004 to 2008 with the lowest value reaching to − 1.754 for the year 2008 (Fig. 2c). The trend line was also insignificant for the concerned series. A higher number of meteorological stations (93.33%) showed positive trends for the index. Unlike humid and sub-humid climate

Fig. 2 Temporal evolution of SPEI calculated at a time lag of 12 months in **a** Kazakhstan and the constituting climate zones—**b** sub-humid, **c** humid, **d** semi-arid and **e** arid

(a) Kazakhstan

(b) Sub-humid

(c) Humid

(d) Semi-arid
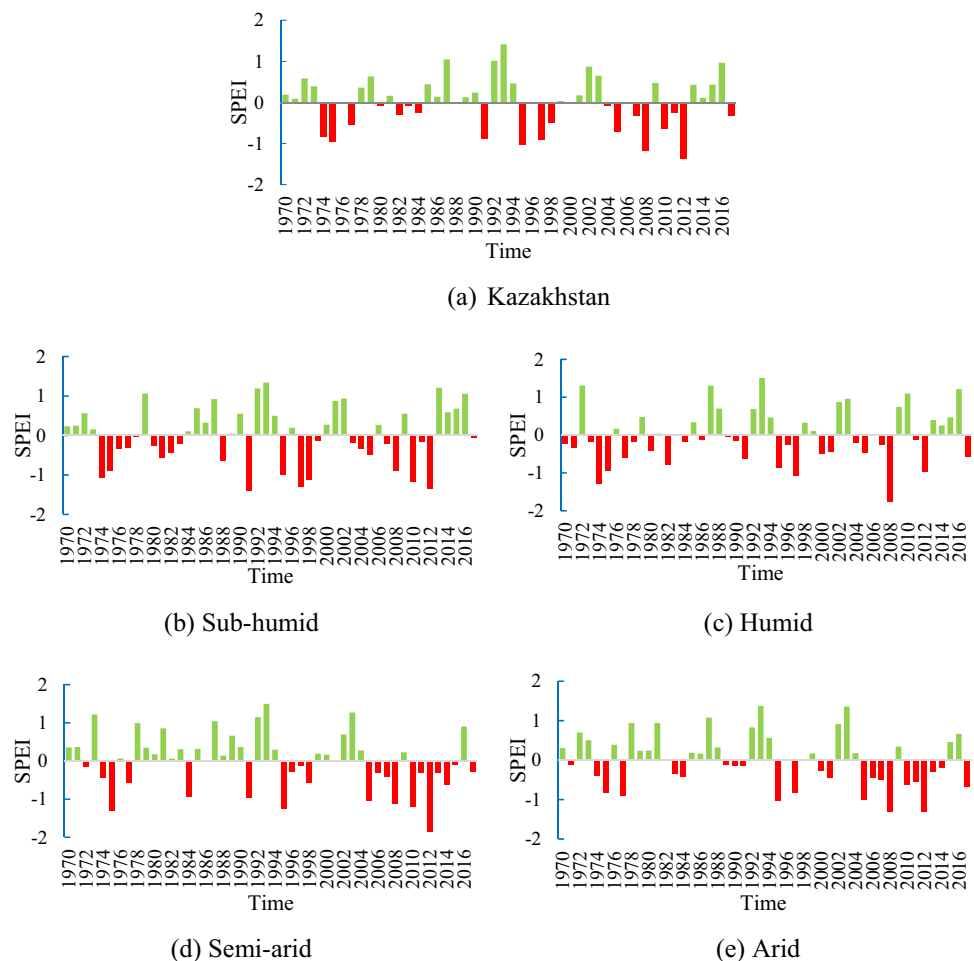
(e) Arid

regions, the arid region showed a significant downward trend for the SPEI 12 values indicating the drying tendency of the arid area. The Mann–Kendall statistic for the time series was − 1.875 ($p < 0.10$) with a slope of − 0.013 units per annum for the desert sub-region. The SPEI 12 values were negative from 1995 to 2001 and from 2005 to 2014 except for the years 1999 and 2009 that showed positive values for the index (Fig. 2d). Around 76.46% of the stations located in the climate zone presented downward trends for the index with the least slope values reflected by Tuschibek, Cilli, Akkuduk, Zlikha and Aralskoe meteorological stations. The semi-arid sub-region showed continuity in negative SPEI 12 values from 1995 to 1998 and 2005 to 2017 with only 2 years 2009 and 2016 showing positive values (Fig. 2e). All these negative runs resulted in a strong significant downward trend for the sub-region. The Mann–Kendall statistic for the SPEI 12 series was − 1.929 ($p < 0.05$) with a downward slope of − 0.012 units per annum for the series. The negative peak with the lowest magnitude for the area was reported by the year 2012 for which the SPEI 12 value reached as low as − 1.834. All the meteorological stations reported negative

trends for the SPEI with the lowest slopes presented by Turgay, Taipak, Zhalpaktal and Irgiz meteorological stations.

To evaluate the seasonal change through time, SPEI calculated at a time lag of 3 months (SPEI 3) were analysed for the selected sites across the territory of Kazakhstan. For the spring season, the M–K statistic ($z = − 0.684$) showed a downward trend for the study area with negative peaks dominating in the latter half of the time period especially in the spring of 1995, 1997, 2001, 2008 and 2012. For the summer season, the time period from 1994 to 2017 observed more intensive summer droughts with SPEI magnitude well below -0.9 for most of the peaks. The season showed an insignificant downward trend by giving an M–K statistic of − 0.471. The M–K test statistic ($z = − 1.057$) calculated for the autumn season showed the drying tendency of Kazakhstan during the studied time period. Strong negative peaks were reported in the autumn of 2005 and 1997 at − 1.42 and − 1.33, respectively. The winter season in Kazakhstan showed an insignificant wetting ($z = 1.039$) tendency during the time period from 1970 to 2017. Most of the negative peaks in the winter season

were concentrated in the time slice from 1970 to 1994. The lowest SPEI 3 value was reported in the winter of 2012 at a magnitude of − 1.34.

Of the total negative peaks with SPEI < − 0.5 that were observed during the spring season of sub-humid climate zone, only 36% of the peaks were reported after 1994 while as 64% occurred before 1994 with most of them concentrated in the 1970s. Moreover, the high-intensity peaks were also reported before 1994 for the season with the lowest peak of − 1.76 in 1991. The M–K statistic showed an insignificant drying tendency of the climate zone during the spring season. Summer and winter seasons reflected more or less a similar temporal evolution of SPEI values for the climate zone. The SPEI values fluctuated between several highs and lows through time during the seasons, ultimately resulting in an insignificant wetting tendency of the climate region during the two seasons. The autumn season showed a clear increase in the number of negative SPEI (< − 0.5) peaks especially after the year 1996, but the inconsistency of the intense peaks generated an insignificant downward trend for the season. In the humid climate zone encompassing the southeastern mountainous region of Kazakhstan, all the seasons with the exception of the spring season showed an insignificant upward trend for the SPEI time series. The spring season showed an insignificant downward trend with most of the SPEI < − 0.5 peaks occurring after 1996. Autumn season also showed a good number of negative peaks after 1995; however, the trend was pushed up by the positive peaks of the years situated towards the end of the chosen time frame. Most of the negative peaks dominated during the 1970s for the summer season and the1980s for the winter season. For the semi-arid climate zone, the spring and winter seasons showed an insignificant upward trend for the SPEI series. In spring season, the SPEI < − 0.5 peaks dominated during the 1970s and 2010s. Similarly for the winter season, the SPEI < − 0.5 values dominated from 1974 to 1977 and from 2008 to 2012. A strong dominance of SPEI < − 0.5 peaks was reported by the summer season of the years 2006–2012 with the exception of 2009 and again for the years 2014, 2015 and 2017. All these peaks towards the latter half of the studied time period generated a negative M–K statistic of − 1.9 in the season resulting in a significant trend ($p < 0.10$) for the semi-arid climate zone. In the autumn season, the negative peaks falling in a particular drought level dominated from 2001 till 2013 with only 2006 showing a positive SPEI value. The associated negative trend was significant ($p < 0.05$) with the season's SPEI series giving an M–K statistic of − 2.10. For the arid climate zone, all the seasons showed a progressive increase in the number of negative peaks especially after the year 1994. The M–K statistics showed a downward trend for all the seasons except the winter season for which the SPEI time series showed a positive trend. A significant negative trend was reflected by

the spring season ($p < 0.10$), however, the trends were insignificant for summer, autumn and winter seasons.

Shortage of precipitation is considered the major factor responsible for creating water deficits and hence dry spells over varied time scales (Liu et al. 2015). However, temperature plays a pivotal role in inducing drought conditions by increasing the process of evapotranspiration with profound impact over areas receiving meagre precipitation. A significant warming trend witnessed by the country (Salnikov et al. 2014; Kazhydromet 2017; Nyssanbayeva et al. 2019; Farooq et al. 2021) during the recent past has a strong influence on the calculated SPEI tendencies. Relating temperature and precipitation anomalies with SPEI series computed at various time lags reflected that precipitation change plays a stronger role in producing various kinds of dry and wet spells than the temperature in different seasons in Kazakhstan as well as over its constituent spatial units. For instance, a significant increase in precipitation along with an insignificant increase in temperature during the winter season was responsible for producing a wetting tendency in the territory during the studied time frame. The SPEI trends shown by humid and sub-humid climate regions are also strongly controlled by the precipitation quantities received over a given period of time in different years and seasons. Similarly, a significant rise in autumn temperature discouraged the wetting trend in the arid and semi-arid climate regions of the territory despite small increases in precipitation reported from various sites located in the regions. The effect of temperature is more visible in the arid and semi-arid climate zones with comparatively little influence reported from humid and sub-humid climate zones. In other words, the upward trend of temperature across various climate regions in Kazakhstan have a strong tendency to make droughts worse by increasing their characteristic properties such as peak, duration, intensity and severity. A general increase in the number of heatwaves in the recent past has the potential to drive the constituent areas towards a drier climate (Kazhydromet 2017). The annual and seasonal fluctuations shown by the SPEI values can be attributed to similar causal factors. Intense heat waves during the mid-1990s encompassing several regions of Eurasia aided in generating many dry events in the latter half of the decade (Karatayev et al. 2022). Soaring temperatures during the summer months (June to mid-August) of 2010 encouraged the dry spells across the country (Karatayev et al. 2022). Insufficient precipitation in the winter season of 2012 (FAO 2021b), adverse weather conditions during the early autumn of 2014 especially over the north-western parts (FAO 2021b) were responsible for the lowest dips in SPEI values.

A comparison of the occurrence probability of various levels of droughts including the total droughts was made by analysing the time series about the point of probable change detected in the year 1994. Figure 3a, b show the probability
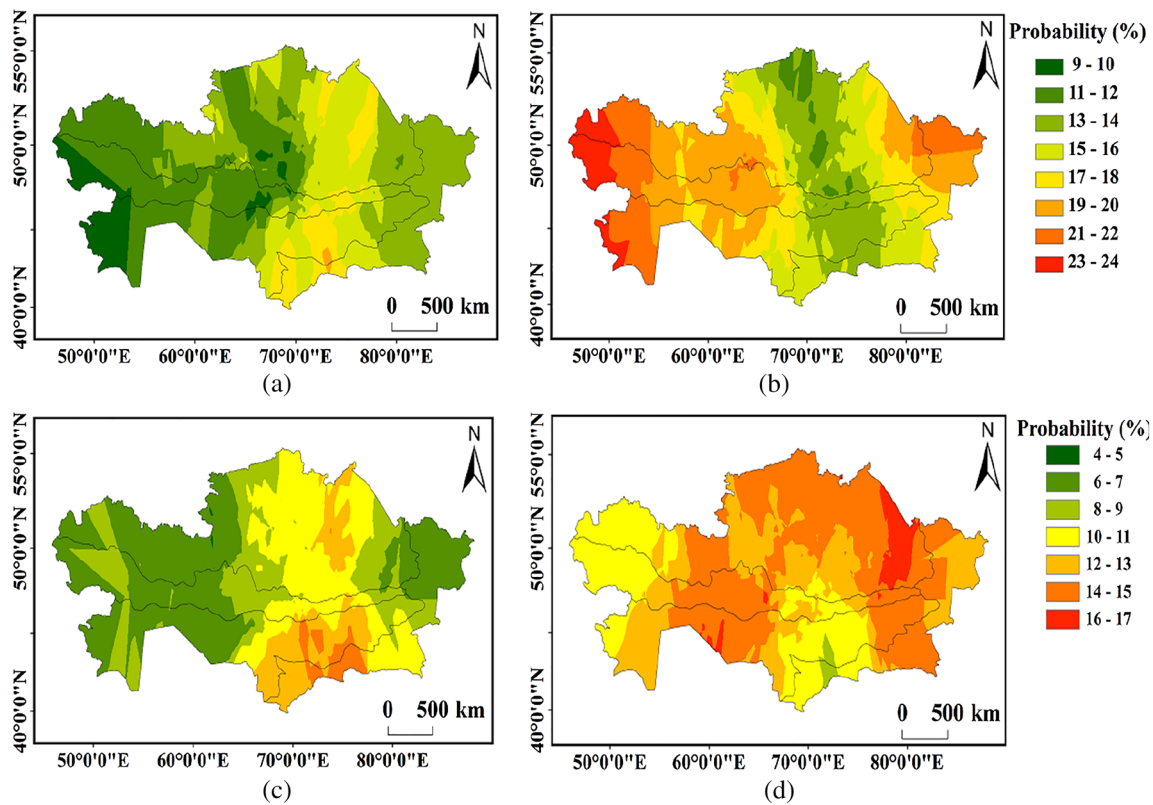
Fig. 3 Comparison of the spatial distribution of probability occurrence of different levels of droughts—mild (**a**, **b**) moderate (**c**, **d**) severe (**e**, **f**) extreme (**g**, **h**) and total droughts (**i**, **j**) during two-time slices ranging from 1970 to 1993 (left) and 1994–2017 (right)

occurrence of mild droughts in the territory of Kazakhstan. In the time slice from 1970 to 1993, the highest occurrence of mild droughts was concentrated along the central longitudinal extent encompassing the parts of western humid, central east arid, semi-arid and sub-humid continental climate areas of the country (Fig. 3a). The remaining areas of the mentioned climate regions showed a lower probability occurrence with the lowest possibility dropping to around 9%. The mild drought happening probability rose from 18.05 to 23.41% during the latter time slice with the highest probability centres shifting towards the western parts of all the climate sub-regions except the humid climate region for which the probability centre showed a north-easterly shift. The spatial extent of the lowest occurrence frequency areas for the time slice 1994–2017 more or less superimposed the parts of all the climate zones that showed the highest occurrence probability during the former time slice i.e. from 1970 to 1993 of the studied time period (Fig. 3b). The occurrence probability of moderate drought reflected more or less a similar spatial pattern as was shown by the mild category drought during the time slice of 1970–1993 across different climate units. However, the range of probability was lower at both the extremes in comparison to mild droughts. For the time slice 1994–2017, a higher occurrence of moderate

drought happened along a wide spatial arc encompassing the central and eastern parts of arid and semi-arid climates along with a major part of the northern sub-humid continental climate zone and southeastern humid mountainous zone (Fig. 3c, d). Moreover, the lower extreme of the drought level almost doubled from 4.86 to 8.61% in the latter half of the chosen time period. Upon comparing the two-time slices, the highest possibility of severe drought events shifted from the northwest towards a more southerly location in the sub-humid continental zone and from the western position towards a more central location in the arid and semi-arid climate zones (Fig. 3e, f). Moreover, in the humid climate zone the probability centre shifted from the northeastern part of the region towards the southwestern location during the latter part of the observed time period. The range of possibility for the severe drought level increased from 7.05-1.06% during 1970 and 1993 to 10.69-2.71% during 1994 and 2017. The extreme drought level has seen the lowest possibility increase among all the discussed drought types. The drought type reported a smaller increase of less than one percent at both the highest and lowest extremes. During 1970–1993, the highest occurrence probability was reported from northeastern and central parts of humid climate zone, eastern parts of arid and semi-arid climate zones
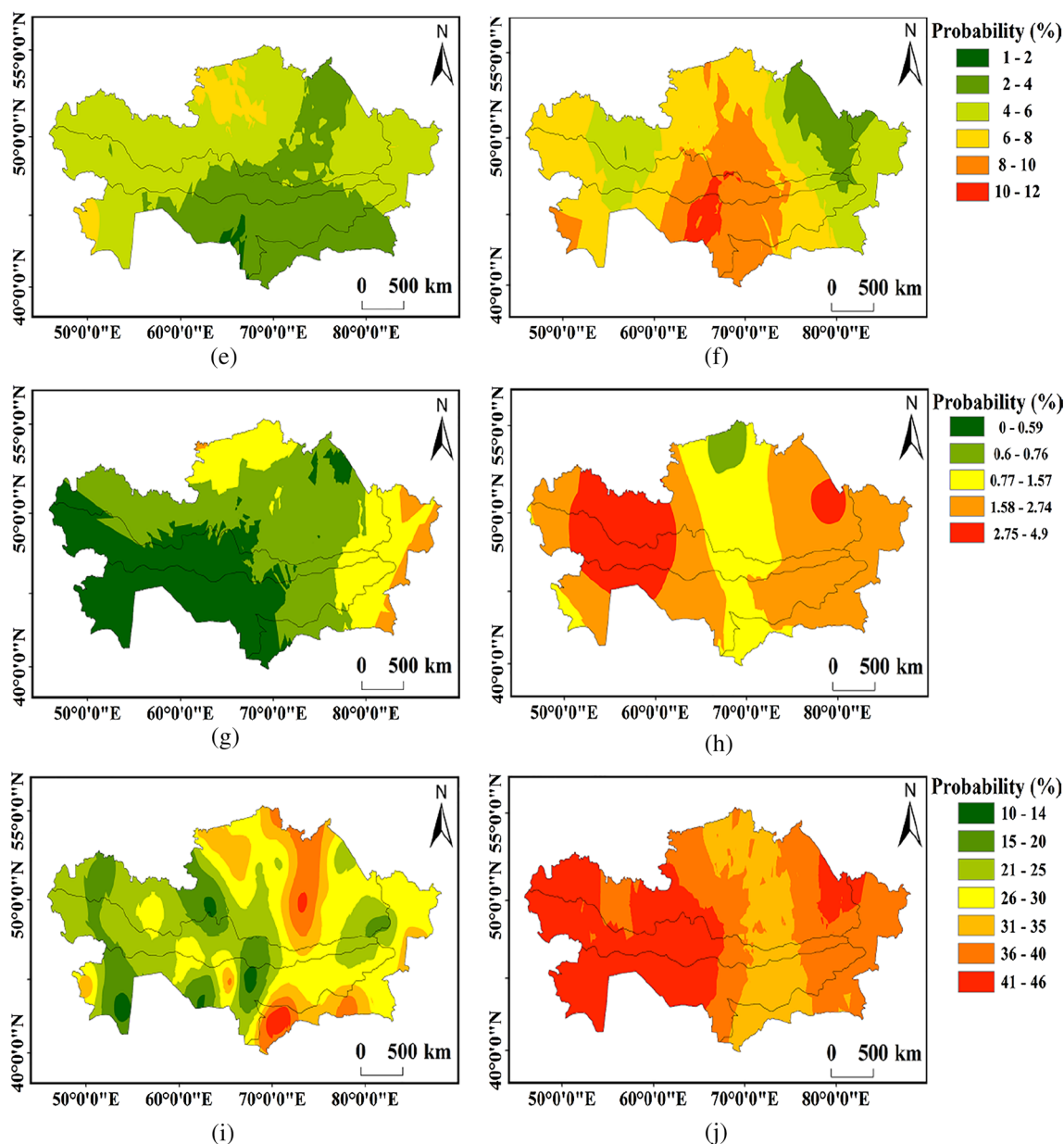
Fig. 3 (continued)

and eastern and northern parts of sub-humid climate zone (Fig. 3g). However, the spatial pattern of the highest possibility percentage shifted towards the eastern and western parts of arid, semi-arid and sub-humid continental climate zones. The humid mountainous climate zone also reported a moderate to high occurrence percentage in comparison to during 1994–2017 (Fig. 3h). Apart from this, the areal coverage has also increased to a considerable degree in the latter time slice. The total drought occurrence possibility showed a strong increase especially at the lower extreme of the percentage bar upon comparing the two time periods (Fig. 3i, j). The spatial distribution of the total drought occurrence

probability during the two-time slices closely resembles the mild drought level, reflecting a greater contribution to the overall droughts across various spatial units.

4.2 Intra-annual Variability of Droughts

Monthly SPEI values (SPEI 1) for the four climate zones of Kazakhstan were analysed in detail to conclude about the intra-annual variations in droughts in terms of distribution, occurrence frequency, shifts in the drought types and drought months through the studied time period. The

dynamics of defined levels of droughts are discussed in detail in the following paragraphs.

In the northern sub-humid region of Kazakhstan, the highest probability percentage for the occurrence of droughts was reported by the months of April and December at a probability of 31.3%. For April more severe droughts were observed in comparison to December. The least probability was reported by May at 16.7%. It was also the only month for which more droughts were reported for the moderate category of droughts than mild. January showed increased evidences of droughts from 1994 with high severity as compared to the incidents reported before 1994. The drought incidents decreased in general for the month of February, March and July. June also showed decreased drought intensity from 1994 with strong domination of mild droughts. The drought frequency increased rapidly for the months of August, September and October with a maximum contribution to the total percentage from 1994 to 2017. It remained more or less same for the first half and second half of the studied time for the month of November. A considerable shift was observed with more

frequent droughts reported by August, September and October after 1994 in the climate zone (Fig. 4a).

In the eastern and southeastern mountainous humid sub-region, the maximum probability percentage for the total drought occurrences was reported by the month of April at 29.2%, followed by September and May for which the percentage was 27.1%. The least percentage was reported by June that showed only 18.8% chances for the occurrence of total droughts. For January, March, April and May the total drought events increased both in frequency and intensity. For July, August and December the moderate droughts disappeared after 1994 and the months were dominated by mild category droughts. For September and October, the frequency of droughts increased rapidly after 1994. For November, mild droughts dominated in the latter half of the time period with no moderate, severe or extreme droughts after 1996. The drought events were evenly distributed through different months and no clear shift was observed for the humid mountainous sub-region (Fig. 4b).

In the semi-arid sub-region, the highest probability percentage for the occurrence of total droughts was shown in the months of January and April for which the percentage
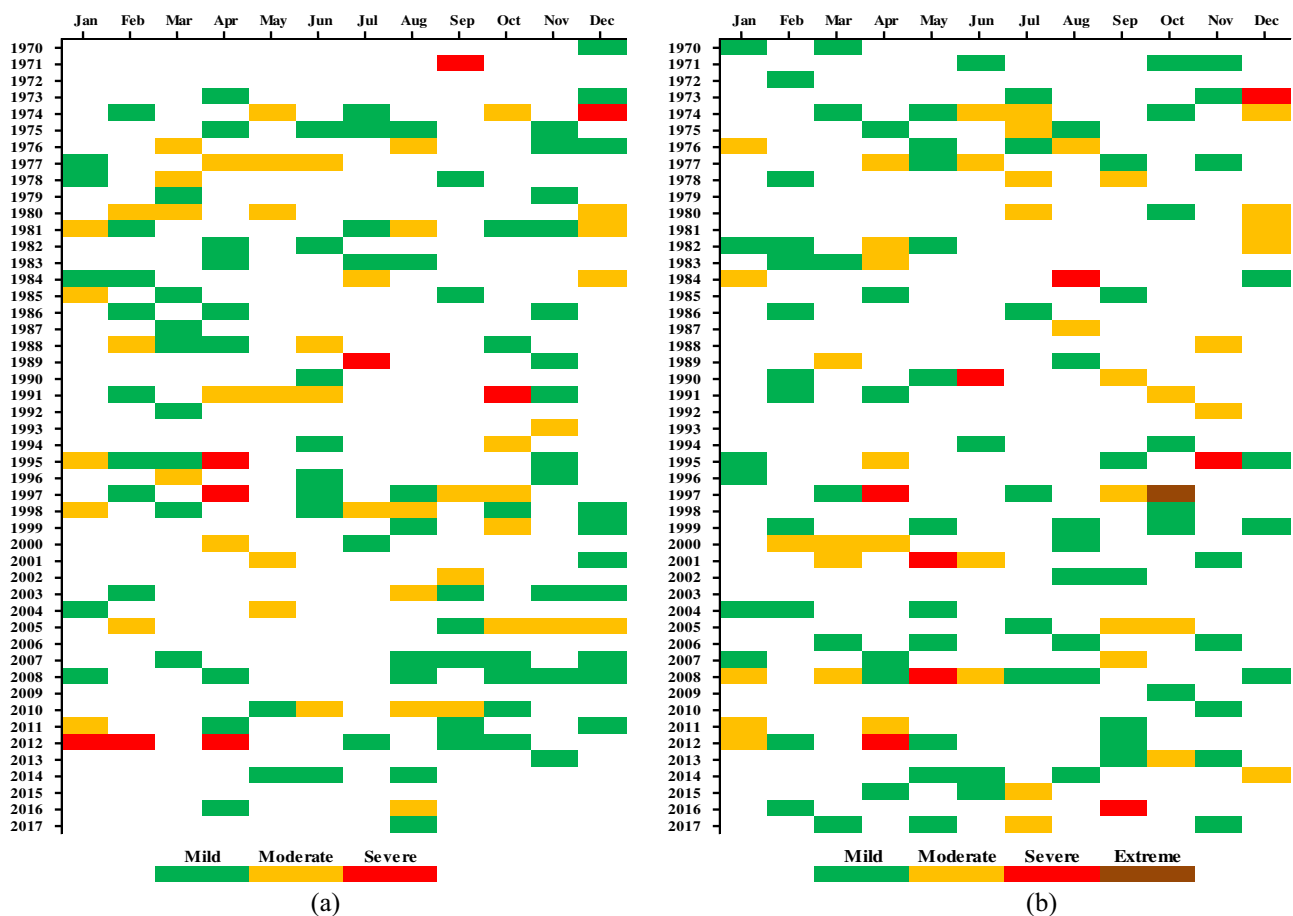
Fig. 4 Distribution of small scale (SPEI 1) droughts in **a** sub-humid, **b** humid, **c** semi-arid, **d** arid climates of Kazakhstan
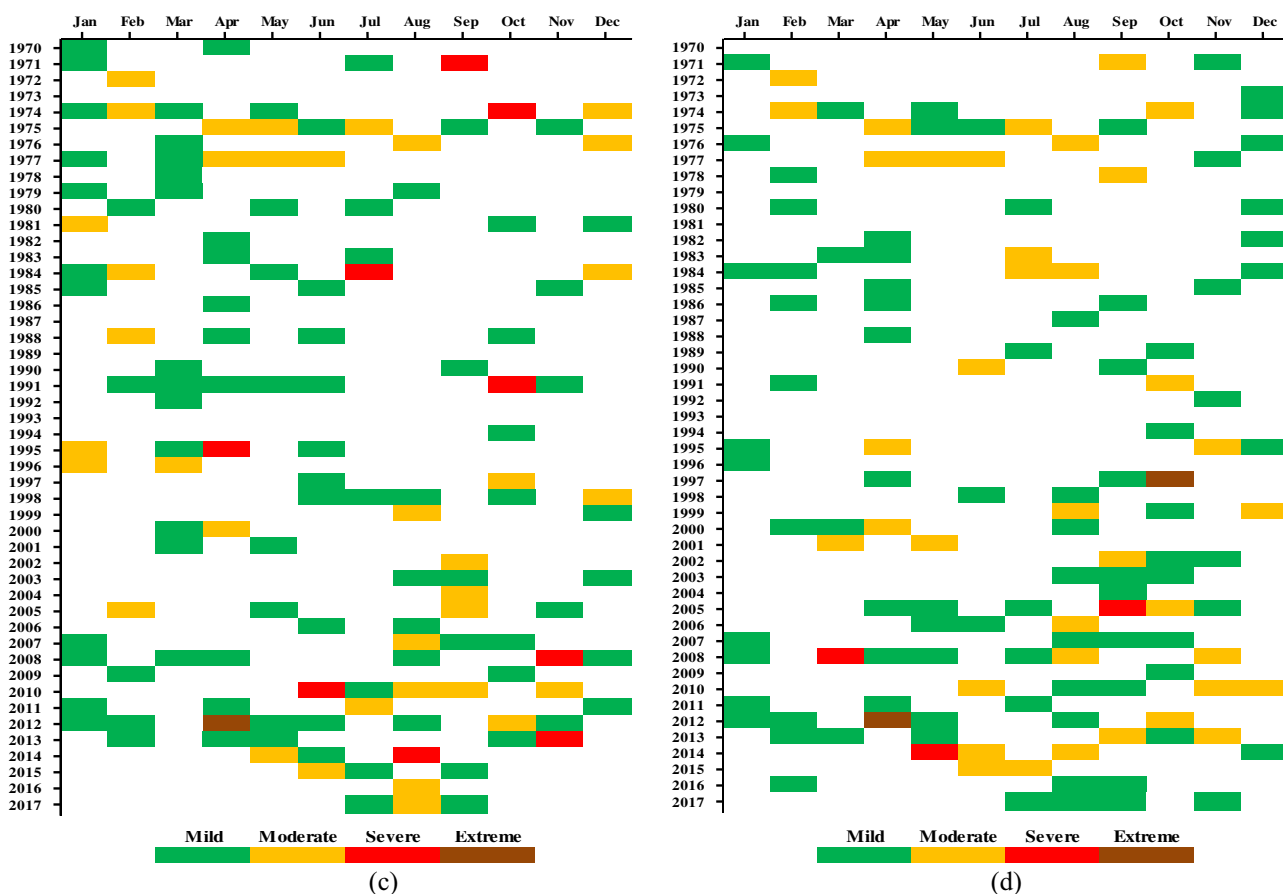
Fig. 4 (continued)

was 29.2%. The maximum contribution to this percentage was made by the years from 1970 to 1994 after which the frequency decreased tremendously for the 2 months. Besides April was the only month that showed all categories of drought events. For February and December, the intensity of the drought months decreased through time. There was an overall decrease in the drought occurrences for the mild drought dominant month of March. For the month of May, the frequency occurrence of mild droughts remained static but the moderate droughts decreased in the count when the time period was folded about 1994. For June both severity and frequency increased from 1970 to 2017. The month of July was symmetric in drought count about 1994 but showed more drought events towards the end of the time period. The drought frequency and severity increased tremendously for the months of August and September more specifically after 1997. Also for October and November, the occurrence frequency increased but the only difference was that October showed severe droughts in the first half of the time period from 1974 to 1991 while November showed the same in the latter half of the time period from 2008 to 2013. Moreover, October showed three drought types—mild, moderate

and severe while as November showed only mild and severe droughts. November with the least probability percentage (16.7%) showed the least frequency of drought occurrence. Before 1994 droughts occurred more frequently from January to June but the trend became the opposite after 1994 when more droughts were reported from July to December (Fig. 4c).

The arid climate zone showed a general increase in the occurrence frequency of droughts from 1970 to 2017. This feature of the climate sub-region became more dominant after 2004. Besides the area was dominated by mild and moderate category droughts from 1970 to 1994 but the pattern changed with the occurrence of severe and extreme category droughts which were observed in the area after 1994. The highest probability percentage of total droughts (including all category droughts) was shown in the months of August and September for which the probability occurrence of droughts was 31.25%. The least probability was shown in the month of March for which the probability of occurrence was only 12.5%. Talking from the perspective of different drought categories, the month of September commanded in the occurrence of mild droughts, August

dominated the moderate droughts, March, May, September dominated the severe droughts, and April, October took lead in extreme droughts. The maximum contribution to the total droughts for the months of August, September, October and November was made by the years from 1997 to 2017. January showed the occurrence of only mild droughts with the maximum contribution from 1995 onwards. February presented the opposite results for which the maximum contribution to dry spells was made by the years from 1970 to 1991. For the month of March especially after 2000, the SPEI values became more negative resulting in the occurrence of moderate and extreme droughts. The severity of droughts for April increased after 1994 and the droughts fell into the mild, moderate and extreme categories. The droughts increased in both May and June after 1997. For December the frequency of the droughts decreased but the severity increased through time. Apart from this, there was a clear shift in the occurrence of drought months that were concentrated in the late summer month of August and the early autumn months of September and October after 1997 (Fig. 4d). However, before 1997 the drought months were more concentrated in the winter and spring months of the year.

4.3 Discussion

With impacts over diverse biophysical and socioeconomic systems, droughts have become a growing concern in Kazakhstan (Kazhydromet 2017; Farooq et al. 2021). Depending entirely on the precipitation received particularly during the growing season, the cultivation of crops in northern parts of the country is highly vulnerable to dry spells (World Bank 2016). For instance, the wheat production in the country reduced by around 21%, 31% and 36% in the drought years of 2004, 2010 and 2012 (FAO 2021a) mostly due to insufficient precipitation received in the cultivated areas (Xu et al. 2016; Morgounov et al. 2018). Similar damages to the agricultural sector by prolonged dry periods were reported for numerous years during 1986 to 2006 which in particular included the drought years in the second half of the 1990s decade (World Bank 2006; FAO 2008). Hydrological droughts have the potential to affect the southern parts of Kazakhstan such as Almaty, South Kazakhstan and Kyzylorda oblasts by limiting the water supplied for irrigating the crops cultivated in the region. Some water-intensive crops such as cotton and rice grown in the region are also highly vulnerable at times of extended drought periods. Moreover, droughts have a negative influence on raising livestock in the country by severely restricting the availability of water and fodder for the cattle and due to extreme heat resulting from enhanced temperature (Dubovyk et al. 2019). Local changes resulting from unchecked human activities such as diverting the water supply of feeder tributaries of the Aral

Sea basin for irrigation purposes have increased the continentality of the surrounding basin region (World Bank 2016; Issanova and Abuduwaili 2017). The desiccation of the Aral Sea floor altered the precipitation pattern of the region, thus increasing the tendency of the area towards dryness. The catchment witnessed a significant increase in the frequency of drought occurrences characterised by greater severity and extended duration during the recent past (Guo et al. 2018). The drought of 2000–2001 significantly lessened the water inputs to the Aral Sea with an average inflow of only 2.3 km^3/year in comparison to the decadal averages of 9 km^3/year for 1990s and 12 km^3/year for 2000s (Micklin 2016). Similarly, a reduction in the total annual precipitation especially in the sandy Moiynkum, west Kazakhstan and Lake Zaysan basin have also accelerated the occurrence of dry periods (World Bank 2016; Fehér and Fieldsend 2019). Moreover, desertification/land degradation and land use changes have also the capacity to affect the magnitude and frequency of droughts particularly hydrological droughts to a significant degree (FAO 2017). Two-thirds of the land area of Kazakhstan is potentially under threat of desertification (World Bank 2013). Climate-driven desertification is prominent in western parts of the country, which in particular includes the provinces of Atyrau, Aktobe, Mangystau and West Kazakhstan (Hu et al. 2020). The study would like to suggest that competent authorities to take steps in mitigating the issue of climate change that fuels such extreme events and intensifies their existence. Managing surface and subsurface water resources in an arid, semi-arid environment is the primary requirement to combat frequent dry spells in the country. Relying on a specific water resource will not be beneficial in the long run, more water resources especially the most secure ones should be tapped for irrigation and industrial usage. Efficient water-saving methods of irrigation for agricultural land need to be promoted for their wide utilisation to reduce the impacts of droughts. Water conservation methods should be put to use especially in the northern parts of the country practising rainfed cultivation. Lessons need to be learnt from one of the most significant environmental disasters—the desiccating Aral Sea floor and the consequences thereof.

5 Conclusions

The current study investigated the spatial and temporal evolution of droughts by considering specific time lags relevant to the study. The research used SPEI to detect the deviations presented by the time series associated with the selected climate zones on multiple time scales. The results of the study revealed a significant increase in the probability of occurrence of all levels of droughts in Kazakhstan. The long-term trends carried out for several climate subregions reflected

a significant drying tendency for the already water deficit regions of arid and semi-arid climates of Kazakhstan. However, the tendency was opposite for humid and sub-humid regions of the country that showed an insignificant wetting trend during the studied time period. A clear spatial shift in the intensive drought centre for the total droughts was observed when the time period was studied for two-time slices of 1970–1993 and 1994–2017. During 1970–1993, the highest occurrence probability of the overall droughts was concentrated in the northern and southern parts of the country that shifted towards the western and northeastern parts of the country during the subsequent period. April, August and September were recorded as the months with the highest occurrence probability of total droughts in different climate zones of Kazakhstan. Significant increase in temperature, a natural deficit of precipitation and altered precipitation regimes due to climate change have a strong potential to make the country more prone to droughts. The study is significant as it would help the competent authorities in prioritisation of sub-regions based on drought risk and hence frame relevant policies to manage the potential risks resulting from the dry events.

Declarations

Conflict of interest The authors declare no conflict of interest.

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