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Response of the water level of the Balkash Lake to the distribution of meteorological and hydrological droughts under the conditions of climate change

Sayat Alimkulov [a], Lyazzat Makhmudova [a], E. K. Talipova [a,*], Gaukhar Baspakova [a], Dimitris Tigkas [b] and Isakan Gulsaira [a]

[a] Institute of Geography and Water Security, Kabanbai batyr/Pushkin st. 67/99, Almaty, Kazakhstan
[b] Laboratory of Reclamation Works and Water Resources Management, National Technical University of Athens, 15780 Athens, Greece
*Corresponding author: E-mail: elmira_280386@mail.ru

SA, 0000-0003-3236-2084; LM, 0000-0001-8614-7262; EKT, 0000-0001-7092-3167; GB, 0000-0002-3795-0259; DT, 0000-0002-2001-259X; IG, 0000-0002-1451-7487

ABSTRACT

Hydrological droughts occur due to a variety of hydrometeorological phenomena, such as a lack of precipitation, reduced snow cover, and high evaporation. The values of these factors vary depending on the climate and the severity of drought events. Droughts caused by a lack of precipitation and continuing in the warm season have a longer periodicity. This important statement raises the question of whether climate change may exacerbate the phenomenon of drought. Therefore, understanding the changes in the formation of hydrological droughts is key to foreseeing possible changes in the future. This scientific study analyses the spread of hydrometeorological droughts in the Ile-Balkash basin using standardized precipitation indices and the drought index of river runoff. Lake Balkash plays an important role in the hydrological cycle and is a valuable freshwater resource, especially in dry years. Prolonged droughts in the area have serious consequences, such as deterioration of water quality and loss of wetlands, which are important to the ecological system and migratory birds. The analysis shows that during the period of instrumental observations, several extreme hydrological droughts were observed in this area (1943–1946, 1973–1975, and 1983–1987), which emphasizes the relevance and importance of scientific research on the problem of drought.

Key words: climate, hydrological drought, lake level, standardized precipitation index, streamflow drought index

HIGHLIGHTS

- For risk assessment and development of drought adaptation strategy.
- Water resource managers highlight the need for coordinated international governance, especially in the context of climate change and growing challenges.
- Discussion of the relationship between climate and hydrological processes.
- Droughts can have a negative impact on ecosystem stability.
- To develop methods for assessing and predicting hydrological droughts.

1. INTRODUCTION

Droughts are among the most common and severe natural disasters worldwide due to their frequency, wide range of impacts, and long duration. Most often, they arise due to water shortage, which can be the result of the interaction of various factors, such as weather conditions (precipitation deficit), hydrological, hydrogeological, or water management factors (Wong *et al.* 2013; Jiang *et al.* 2020; Yerdelen *et al.* 2021).

According to the classification (Wilhite 2000; Dai 2011) droughts can be divided into meteorological, hydrological, agricultural, and social-economic, as they indicate water shortage, which is caused by an imbalance between the demand and supply of water for various activities. Meteorological droughts caused by deficient precipitation over a long period of time are the driving force behind other types of droughts. For example, lack of rainfall leads to decreased river flow and insufficient groundwater recharge.

Hydrological droughts occur when river flow and water reserves in aquifers, lakes and reservoirs are below long-term average values. Hydrological drought usually occurs with a delay compared to meteorological drought. Regions are interconnected by hydrological systems; therefore, the area of distribution of hydrological drought could be greater in extent than the area of meteorological drought that caused it. Identifying the relationship between hydrological droughts and climate-related precipitation deficits is often complicated by the simultaneous impact of other factors on the hydrological characteristics of the basin, such as ineffective water resource management, changes in land use (land degradation, soil erosion), as well as the construction of reservoirs and dams (Salnikov 2020).

As a result of climate change, extreme droughts have become more frequent worldwide (Trenberth *et al.* 2013; Mukherjee *et al.* 2018; Ault 2020), especially in Central Asia (Guo *et al.* 2018; Chen *et al.* 2019; Salnikov 2020), which is one of the driest regions of the world. The increasing intensity and frequency of droughts are one of the key factors that affect sustainable economic development and environmental security. Thus, the occurrence and impact of drought in the context of climate change is an important research topic that has received additional attention from scientists (Nam *et al.* 2015; Ukkola *et al.* 2020; Haile *et al.* 2020).

The increase in drought due to climate change and anthropogenic factors increases the impact on the hydrological cycle in countries with a water crisis, especially in countries with drainless basins and lakes that do not have access to the oceans. Drought monitoring, i.e. determining the time of its onset and end, and its types, is of great importance in planning and managing water resources (Salnikov 2020). Most of Central Asia is a giant drainless region (more than 6,000 lakes with a total area of 12,300 km^2). The drainless lakes of Central Asia include the Aral Sea and the lakes Alakol, Ebinor, Lobnor, etc., including the Ile River basin and Lake Balkash (Savvaitova & Petr 1992; Che 2019).

Ile-Balkhash watershed originates in the high mountains and is almost entirely fed by glaciers, snow cover and precipitation and its lower reaches contrast sharply with hyper-arid (extra-arid) deserts. The problem of drought is relevant in this region and according to the authors (Yegizbayeva *et al.* 2024), drought has affected about 44% of the Balkash Lake basin (including the territory of Kazakhstan and China). According to the authors, severe agricultural droughts occurred in 2000, 2008, 2014 and 2015, highlighting the region's vulnerability. Any type of drought in this region has significant impacts on water resources, agriculture and food security. In addition, changes in the river flow regime, rising temperatures, changes in the nature of precipitation and increased anthropogenic factors have a complex impact on the optimal level of Balkhash Lake, which is very important for the country.

Understanding how meteorological droughts transform into hydrological droughts is critical for managing hydrological droughts. However, most studies have focused on aspects of the distribution of meteorological and hydrological droughts in river basins and much less attention is paid to how these droughts affect the level and area of the lake, its flora and fauna.

As long as the lakes are an important part of the hydrological cycle, especially in arid, drought-subjected regions and store large amounts of freshwater resources, they are of great value to aquatic ecosystems. Long drought in the lake area leads to the death of many aquatic plants, to decrease in the self-purifying ability of the lake and deterioration in water quality and could also lead to the drying out and destruction of a significant part of the wetlands (Havens *et al.* 2007; Sobhani *et al.* 2019; Perales *et al.* 2020).

Wetlands play a vital role in maintaining ecological balance, reducing droughts, preserving water sources, and water and soil loss and providing environmental, economic and social benefits for human survival and development (Zang *et al.* 2016). Since 2012, the southern part of Balkash Lake and the Ile River delta have been included in the list of wetlands of global importance under the Ramsar Convention (Tesch & Thevs 2020). According to UNEP (United Nations Environment Programme), the number of migratory birds has almost halved over the past 30 years, as they are at greatest risk during the migration season, so the survival rate of their nestling is rapidly decreasing from year to year. Kazakhstan is located on the migration and nesting route of a dozen species of birds, such as pink flamingos, pelicans, cranes and others. Flying across dozens of countries, the birds are affected by the triple planetary crisis associated with climate change, loss of biodiversity and environmental pollution (Imentai *et al.* 2015).

Wetlands in arid landscapes provide vital habitat for millions of migratory waterbirds worldwide. Migratory waterbirds in arid and semi-arid mid-latitudes rely on a limited number of important wetlands to connect continental movements that support annual life-history events (Zang *et al.* 2016). To preserve them, the Ile-Balkash State Nature Reserve was created in June 2018. The Ile-Balkash natural reserve is represented by 32 species of fish, 3 species of amphibians, 19 species of reptiles, 284 species of birds, and 39 species of mammals (Imentai *et al.* 2015).

Since 2004, the United Nations Development Program (UNDP), together with the Government of Kazakhstan with the support of the Global Environment Facility (GEF), has implemented a number of initiatives aimed at the comprehensive conservation of priority globally significant wetlands as nesting sites and habitats for migratory birds in Kazakhstan. In this regard, it is very important to identify hydrological and meteorological droughts in the region of river basins and lakes, since it is not surprising that drought is one of the factors causing changes in the level and area of lakes, which in turn plays an important role in maintaining the ecological system of this region. The following drought indices are used to determine hydrological drought in the lake basin: Standardized Precipitation Index (SPI) and Streamflow Drought Index (SDI) (McKee *et al.* 1993; Shukla & Wood 2008; Li *et al.* 2016).

The purpose of this scientific research is to consider the phenomenon of hydrological drought in the Balkhash Lake basin, to study meteorological and hydrological patterns of drought distribution and to determine their relationship with the lake level changes.

2. MATERIALS AND METHODS

2.1. Study area

Balkash Lake belongs to the group of endorheic reservoirs of the arid territories of Central Asia, which are located at the bottom of the plain at the foothills of the surrounding mountain systems. In arid climates, the life of these lakes is supported by the inflow of river water. Water resources are formed high in the mountains, whose landscape includes high mountain glaciers and stone glaciers. The hydrological regime of the rivers of the territory under consideration is determined by climatic conditions, the ratio of river power sources, the nature of the relief, and the hydrogeological features of the river basins (Dostai & Tursunov 1997). The uniqueness of Balkash Lake lies in the fact that it is divided by a narrow strait into two parts with different chemical characteristics of the water – in the western part it is almost fresh, and in the eastern part it is saline (Figure 1).

The lake's watershed covers an area of 413,000 km^2, of which about 15–20% is located in the territory of People's Republic of China. Its length is approximately 600 km, its width varies from 9–19 km in the eastern part to 74 km in the western part. The significant size of the territory, inland location, and orographic and climatic heterogeneity determine a wide variety of natural conditions. According to the nature of the orography, the basin is divided into three parts (Dostai 2009; Dostai *et al.* 2012).

The northern and northwestern part which occupies the main region of the Northern and Northwestern Balkash region is located in the area of Kazakh hummocky terrain. The relief of this part of the basin is characterized by a combination of plains with hills, the slopes of which are dissected by numerous hollows. The tops of the hills rise 30–40 m, sometimes 100–200 m above the surrounding area.

The central part is the Balkash depression. It is an accumulative sandy-desert plain stretching from the southern border of Saryarka to the mountain belt in the south and southeast. In the northern part of the Balkash depression, there is a flat plateau. The prevailing heights here are 400–450 m. The plateau is dissected by hills, knolls, valleys of dry ravines and drying-up rivers. In the southern part of the depression, there are mainly sandy deserts: Taukum, Moiynkum, Saryyesik Atyrau. The slope of the plain toward the lake from all sides is very insignificant, from the south it is only about 0.003°.

The southeastern and southern parts of the basin are occupied by the mountainous region of Zhetysu Alatau and the northern ranges of the Tien Shan mountain system. The mountain region of Zhetysu Alatau (in the limits of Kazakhstan) includes the Tarbagatai ridge, Urkashar and Zhaiyr hills, Barlyk and Maily ridges, Zhetysu Alatau ridges with altitudes of 2,000–4,000 m.

The Ile depression, dividing Zhetysu Alatau and Borokhoro mountain systems from the eastern part of the Northern Tien Shan, stretches for hundreds of kilometers from the Kulzha oasis in Xinjiang to the Kapshagai gorge. Its absolute heights vary from 600 m near the Kazakh-Chinese border to 500 m in the area of the Kapshagai hydroelectric power station dam site. Approximately in the middle, this section of the Ile depression is divided by Katu and Kalgan hills on the right bank and Bugyty mountains on the left bank and is divided into two independent depressions. In the western part, the Ile depression is closed by Karaoy and Itzhon plateaus (Sokolova 1989; Dostai *et al.* 2012).

The sources of surface watercourses of the considered territory are mainly located in the mountainous areas surrounding the region – the mountain ranges of Tien Shan, Jungarian Alatau and Tarbagatai. From the eastern and southern parts of Balkash Lake the largest tributaries originate from the mountain formations of the northern part of the Ile Alatau, Jungarian Alatau and Tarbagatai. Ile River provides the biggest part of the total flow; there are also smaller rivers – Karatal, Lepsi,

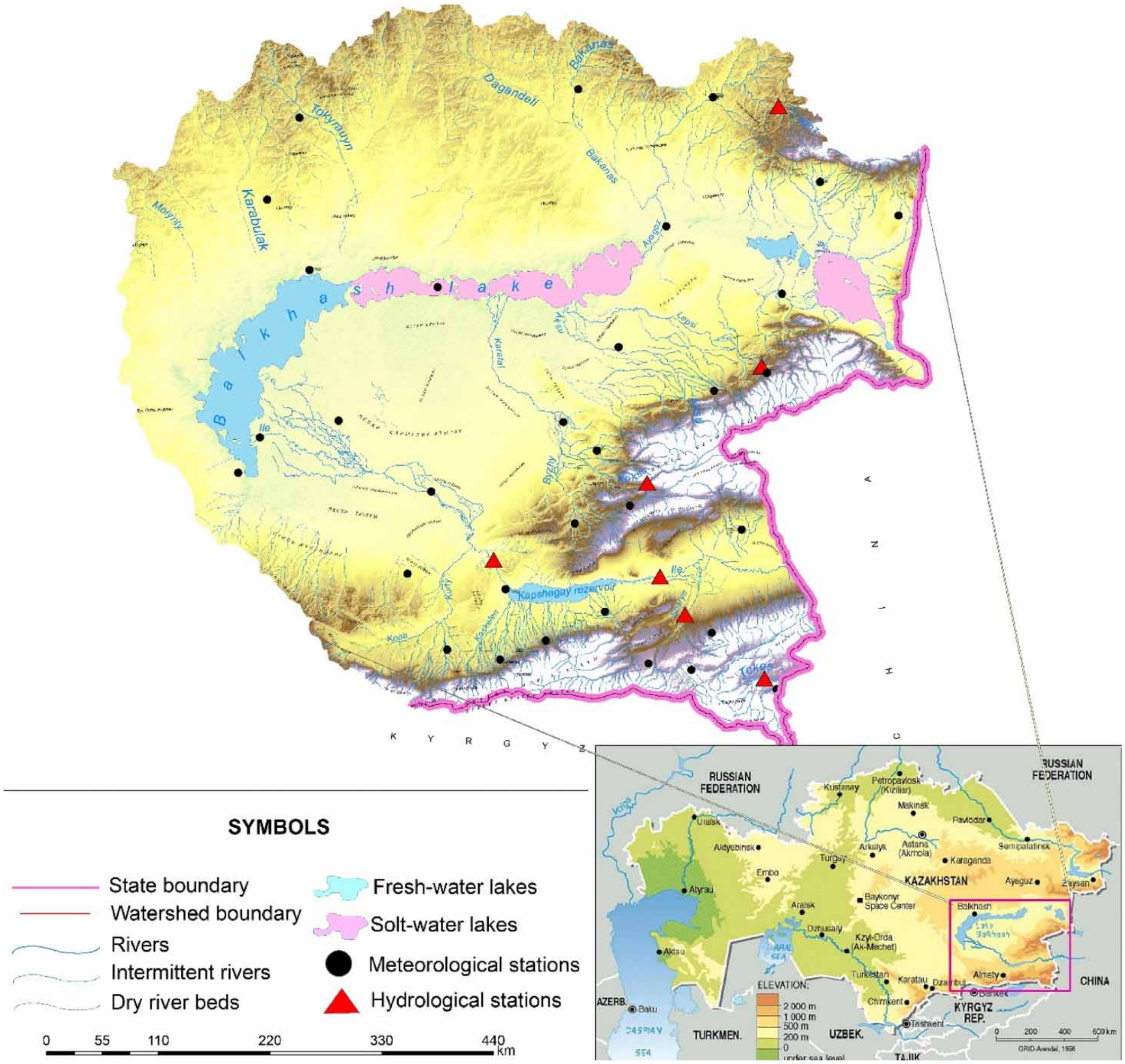

Figure 1 | Schematic map of the Balkash Lake basin.

Aksu and Ayagoz. With the exception of Ayagoz, all of them are full-flowing arteries carrying large amounts of water and are especially high-water in the summer due to the intensive melting of glaciers in the mountains. From the west and north, the Mointy and Tokrar rivers flow into the lake, having active flow only in the upper reaches and having huge dry valleys which are completely waterless throughout the year with the exception of a short period of spring snowmelt. The unevenness of river flow is noticeably reflected in the level of Balkash Lake, which is subject to significant fluctuations.

The river's water regime is mainly determined by climatic conditions, namely the regime and amount of precipitation, distribution of air temperature, evaporation, share of river feeding sources, nature of the relief as well as hydrogeological and other features of river basins. One of the main factors of runoff is the topography of the basins and, above all, the absolute height. With the change in the absolute height of the catchment, climate factors and underlying surface change consequently change the feeding conditions of the rivers. While glaciers and snow play a significant role in feeding rivers in high mountain regions, in the mid-mountain and foothill zones the importance of seasonal snow cover, liquid precipitation and groundwater increases significantly (Sokolova 1989; Dostaev *et al.* 1997; Dostai 2009).

2.2. Data

To study meteorological and hydrological droughts in the area under consideration, the data on atmospheric precipitation and river flow were used. Meteorological and hydrological data were atmospheric precipitation series from 21 meteorological stations (MSs) and runoff series from 8 hydrological stations (HSs) located in the Balkash Lake basin. Systematic observation data were taken from the materials of RSE 'Kazhydromet' (from the beginning of instrumental observations until 2020 inclusive).

2.3. Research methods

The SPI

The SPI, recommended by WMO for drought monitoring (WMO 2009) was proposed by McKee *et al.* (1993) and is based on the use of time series of monthly precipitation amounts. The calculation procedure involves transforming the precipitation time series using a gamma distribution and then normalizing the resulting probabilities into a SPI:

$$\mathrm{SPI} = F^{-1}G(R) \tag{1}$$

where G is the integral gamma distribution function; R is the amount of precipitation; F^{-1} is the inverse normalized Gaussian distribution.

Positive SPI values indicate humid conditions. Negative SPI values represent dry conditions; the lower the SPI, the drier the time period under study. Precipitation time series for calculating SPI must be sufficiently long, at least 30 years. Since the SPI is associated with probabilities, for each specific location the probability of drought of a certain intensity can be determined. The beginning of drought can be determined when the SPI value drops below −1.0, and the end of drought is determined by the time the index becomes positive. Drought intensity should be calculated as the sum of all SPI values during the drought period.

The SDI

The SDI is a method developed by Nalbantis & Tsakiris (2009) to quantify hydrological drought at different time scales. SDI is estimated using monthly streamflow. Using streamflow $V_{i,k}$, SDI can be determined at different time points q of hydrological year n, using the following equation:

$$\mathrm{SDI}_{i,k} = \frac{V_{i,k} - V_k}{S_k} \qquad i = 1,\ 2,\ \ldots,\ k = 1,\ 2,\ 3,\ 4 \tag{2}$$

where V_k and S_k are respectively the mean and the standard deviation of cumulative streamflow volumes of reference period k as these are estimated over a long period of time. In this definition, the truncation level is set to V_k although other values could be used (Nalbantis & Tsakiris 2009).

Table 1 shows the different drought categories with extreme dry (below −2) and extreme wet (above 2). The number of drought classifications used by SPI and SDI ranges from seven to nine, with some classifications combining moderate wet and moderate drought into one value.

Table 1 | Criteria for interpreting the values of the SPI and SDI indices

SPI value intervals	Characteristics of the category of the territory dryness
≥2.0	Extremely humid
From 1.5 to 1.99	Severe humid
From 1.0 to 1.49	Moderately humid
From 0.0 to 0.99	Slightly humid
From −0.99 to 0.0	Slightly dry
From −1.49 to −1.0	Moderately dry
From −1.99 to −1.5	Severe dry
≤− 2.0	Extremely dry

According to Svoboda & Fuchs (2017), drought occurs whenever the indices drop to −1 or below. The drought ends when the indices reach positive values. Thus, to determine the beginning of different types of droughts, precipitation accumulations are used on the following scales: 1–2 months – for meteorological drought; 1–6 months – for agricultural drought; 6–24 months or more – for hydrological drought. However, a 9-month SPI associates seasonal drought with long-term droughts that can become hydrological, and a 12-month or more SPI is associated with a significant decrease in river waters, reservoir levels and groundwater levels.

SPI and SDI values were calculated for 12- and 24-month periods to determine drought conditions for each station. SDI values were calculated using DrinC (http://drinc.ewra.net/) (Tigkas *et al.* 2015, 2022) and SPI values were calculated using SPI Generator Application software (McKee *et al.* 1993; Edwards & McKee 1997; Ali *et al.* 2020).

3. RESULTS AND DISCUSSION

The water level of the Balkash Lake is characterized by significant cyclic fluctuations caused by fluctuations in the humidity of the territory and, accordingly, by the water balance of reservoirs. The main factor of the lake formation is inflowing rivers. The inflow into the western part of the lake is carried out by Ile River and to the eastern part by the rivers Karatal, Lepsy, Aksu and others. The change in the long-term fluctuations of Balkhash Lake mainly depends on the flow of Ile River (about 80%), since this river belongs to most of the water flowing into the lake.

In modern conditions, changes in reservoir level depend not only on natural factors determining the amount of river flow but also on the operating mode of the Kapshagai hydroelectric power station, irreversible water consumption and construction of new reservoirs in the upper part of Ile River basin in the territory of the People's Republic of China, as well as in the middle part of the basin in the territory of the Republic of Kazakhstan. The second factor in the incoming part of the lake's balance is atmospheric precipitation, which accounts for about 20%. It is very important to take into account long-term changes in these two main factors of the lake's water balance since the moisture content of the territory and drought conditions in the considered area depend on them.

The dynamics of the water level of Balkash Lake are characterized by pronounced directional changes that are long-lasting in nature and according to Figure 2 it is noted that the water level of Balkash Lake was below the critical value twice (341,0 m Baltic System (BS)): in 1946. (340,70 m BS) and in 1987. (340,65 m BS). It should be noted that the BS is a geodetic system that is used to determine altitude relative to sea level in the countries of the former Soviet Union.

In order to consider the situation of Balkash Lake water level below the critical value and determine the factors that influenced this situation, wet and dry periods were determined using the SDI and SPI drought indices. To determine the beginning, end and severity of drought, the monthly precipitation data for SPI at 12- and 24-month scales was used; for

Figure 2 | Dynamics of Balkash Lake water level.

the streamflow, the monthly data for SDI at 12-month scales was used. The results are presented in Figures 3–5 for two indices SPI and SDI for various MSs in the considered basin.

Analysis of the drought characteristics in the Ile-Balkhash basin based on the used aridity indices shows that the spatial distribution of severity, intensity and duration was relatively similar across all hydrometeorological stations, but differed in drought duration. According to the figures, the time course of dry and wet periods based on precipitation and river flow

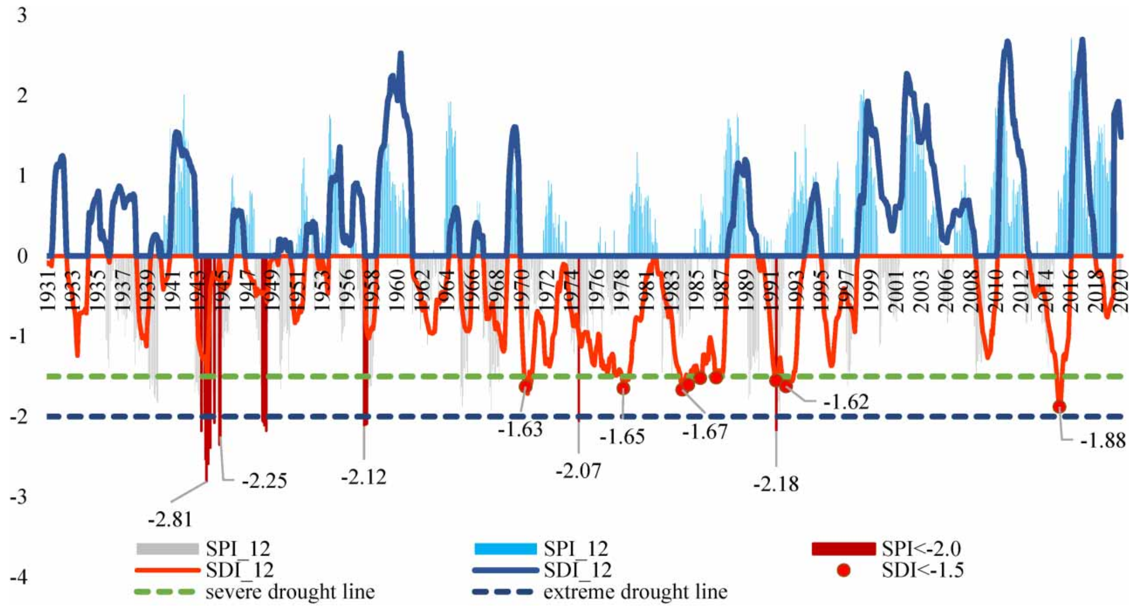

Figure 3 | Hydrological droughts according to the SPI and SDI indices (MS Almaty, HS Ile River – Kapshagay (37 km)).

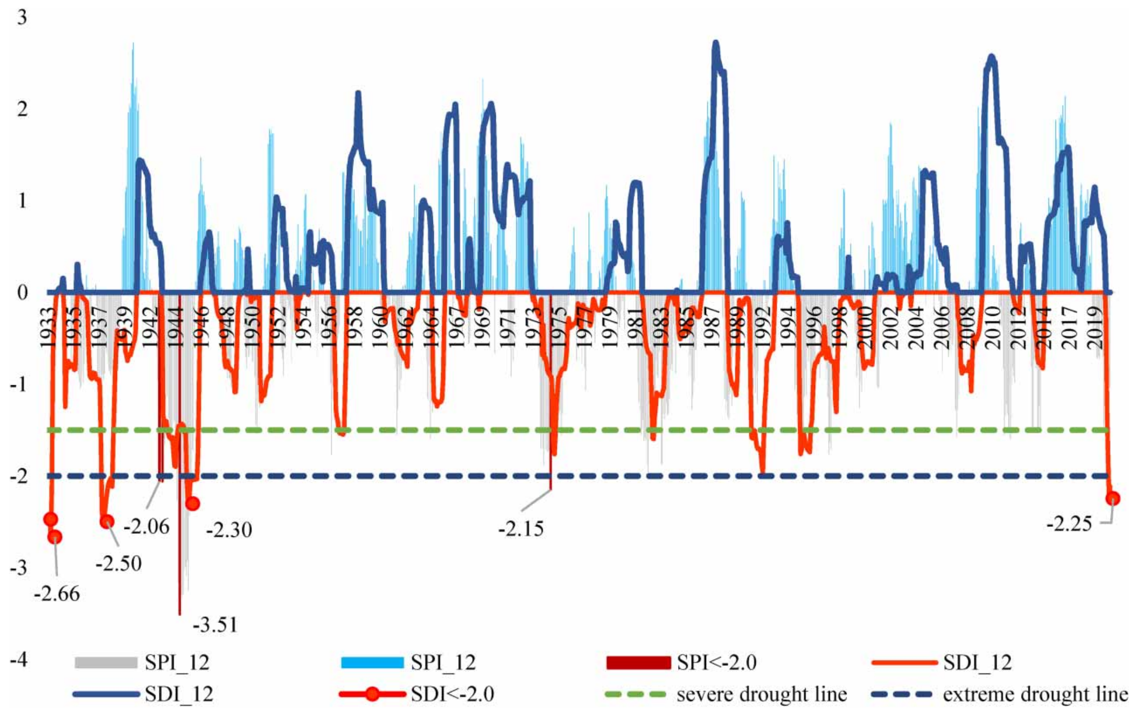

Figure 4 | Hydrological droughts according to the SPI and SDI indices (MS Lepsi, HS Lepsi River – Lepsi city).

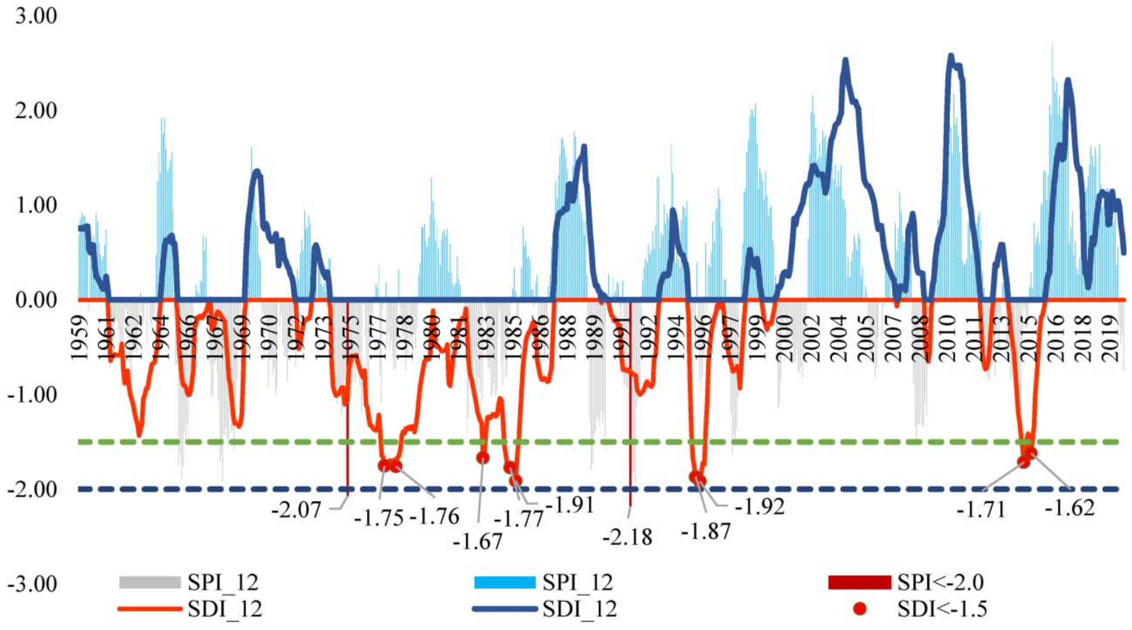

Figure 5 | Hydrological droughts according to the SPI and SDI indices (MS Kyrgyzsai, HS Sharyn River – Sarytogay).

data are synchronous, but the dry period calculated based on precipitation (SPI index) occurs a little earlier compared to the SDI index calculated using river flow data.

In this study, drought is defined as a period of time when the index value is persistently negative and reaches a threshold of -1.0 or lower. In this regard, according to SPI data, the driest period in the Ile River basin and in Zhetysu Alatau (Lepsi, Karatal, Koksu) river basins was the period from 1943 to 1947, when extreme hydrological drought was observed (Figures 3–5), especially in the Southern Balkash region: MS Lepsi – 1944 with an index of -3.51, MS Matai – 1945 with an index of -3.34, MS Sarkand – 1945 with an index of -3.32 (Figure 4).

During the period from 1974 to 1978, the Ile-Balkhash basin was regularly subjected to severe and extreme meteorological and hydrological droughts. The results of scientific research also show that in the time period from 1980 to 1990, there was a dry period compared to other decades, which is confirmed by research (Alimkulov *et al.* 2019); periods of low water were observed in all rivers of the considered basin.

Table 2 shows the parameters of extreme droughts identified by SPI with a time scale of 24 months with values below -2. Analysis of Table 2 shows that in the considered region, the duration of drought varies widely from 141 months (MS Narynkol, 1976–1987) to 7 months (MS Kogaly, 1958), the minimum value of SPI index is -3.91 (MS Zhalanash, 1977–1981).

In the modern period, a large-scale hydrological drought in the considered basin was recorded in the period 1996–1998, lasting 34 months (MS Kuigan). It is advisable to note that in a conditionally natural period, the duration of hydrological drought ranges from 7 months (1930s, MS Almaty) to 36 months (1,040 s, MS Lepsi). The duration of hydrological drought in the modern period has increased for the longer period by 3 times (from 34 months to 141 months).

To visualize the spatial variability of meteorological drought in the Ile-Balkhash basin, two periods were selected (1943–1946 and 1973–1975), which preceded the extreme hydrological drought that contributed to the decrease in the lake level. Analysis of the results obtained using the SPI revealed during these two periods meteorological drought from moderate to extreme at all MSs in the considered area. The spatial distribution map of drought obtained using the IDW method is shown in Figure 6.

In 1943–1946 in spatial terms, the SPI values show that at weather stations located near the lake, moderate drought is observed and in the areas where river flow is formed, the drought values reached extreme values. Consequently, the intensity of drought increases from the branches of the southern part of Kazakh hummocky terrain through Balkash Lake to the north-eastern ridges of the Zhetysu and Ile Alatau. In the period 1973–1975, the spatial distribution of drought had a different character; the areas of the most severe droughts were concentrated in the Northern Balkhash region. Extreme droughts were recorded in the areas of the southwestern part of Tarbagatai Ridge and on the western coast of Balkash Lake (Figure 6).

Table 2 | Parameters of extreme droughts identified by SPI with a time scale of 24 months and with values below −2

Drought beginning	Drought end	Drought, months	SPI_{min}	Total SPI	SPI_{avr}
MS Almaty					
04/1927	05/1929	25	−2.22	−27.59	−1.10
05/1933	09/1934	16	−2.12	−24.23	−1.51
06/1944	**11/1946**	**29**	**−2.45**	**−49.67**	**−1.71**
04/1976	07/1978	27	−2.04	−22.27	−0.82
MS Bakanas					
01/1945	**08/1946**	**19**	**−2.46**	**−30.79**	**−1.62**
04/1976	04/1979	36	−2.08	−32.47	−0.90
11/1996	06/1999	31	−2.75	−48.72	−1.57
MS Kuigan					
08/1945	**06/1947**	**22**	**−2.30**	**−20.61**	**−0.94**
12/1974	12/1976	24	−3.08	−51.82	−2.16
01/1993	11/1993	10	−2.38	−13.39	−1.34
01/1996	11/1998	34	−2.56	−54.16	−1.59
MS Lepsi					
05/1944	**05/1947**	**36**	**−3.65**	**−80.44**	**−2.23**
01/1976	06/1978	29	−2.34	−25.47	−0.88
MS Matai					
08/1944	**05/1947**	**33**	**−3.34**	**−70.93**	**−2.15**
08/1975	05/1979	45	−2.43	−40.01	−0.89
MS Ushtobe					
04/1939	11/1940	19	−2.54	−24.16	−1.27
12/1944	**11/1946**	**23**	**−2.55**	**−41.19**	**−1.79**
05/1975	06/1979	49	−2.16	−68.31	−1.39
10/1997	08/1999	22	−2.08	−18.37	−0.83
MS Kogaly					
02/1958	09/1958	7	−2.02	−8.35	−1.19
10/1962	09/1964	23	−2.08	−31.01	−1.35
02/1976	10/1977	20	−2.25	−19.01	−0.95
MS Sarkand					
05/1944	**10/1946**	**29**	**−3.32**	**−68.71**	**−2.37**
06/1985	**04/1987**	**22**	**−2.08**	**−20.72**	**−0.94**
MS Aksengir					
06/1975	12/1977	30	−2.29	−38.84	−1.29
MS Taldykorgan					
12/1933	09/1934	9	−2.26	−10.92	−1.21
08/1938	10/1940	26	−2.69	−43.27	−1.66
02/1945	**04/1947**	**26**	**−2.32**	**−35.78**	**−1.38**
10/1997	10/1999	24	−2.01	−23.56	−0.98
MS Shelek					
05/1944	**06/1946**	**25**	**−2.60**	**−40.52**	**−1.62**
02/1950	06/1958	100	−2.30	−84.52	−0.85

(*Continued.*)

Table 2 | Continued

Drought beginning	Drought end	Drought, months	SPI_{min}	Total SPI	SPI_{avr}
09/1975	12/1976	15	−2.24	−21.34	−1.42
11/1992	07/1993	8	−2.34	−13.71	−1.71
MS Kyrgyzsai					
05/1944	**04/1947**	**35**	**−3.16**	**−62.46**	**−1.78**
MS Zhalanash					
09/1977	08/1981	47	−3.91	−100.2	−2.13
MS Zharkent					
01/1941	06/1942	17	−2.12	−19.23	−1.13
11/1944	**08/1946**	**21**	**−2.25**	**−29.50**	**−1.40**
06/1968	10/1969	16	−2.44	−21.53	−1.35
01/1941	06/1942	17	−2.12	−19.23	−1.13
MS Narynkol					
03/1976	**12/1987**	**141**	**−2.35**	**−143.4**	**−1.02**

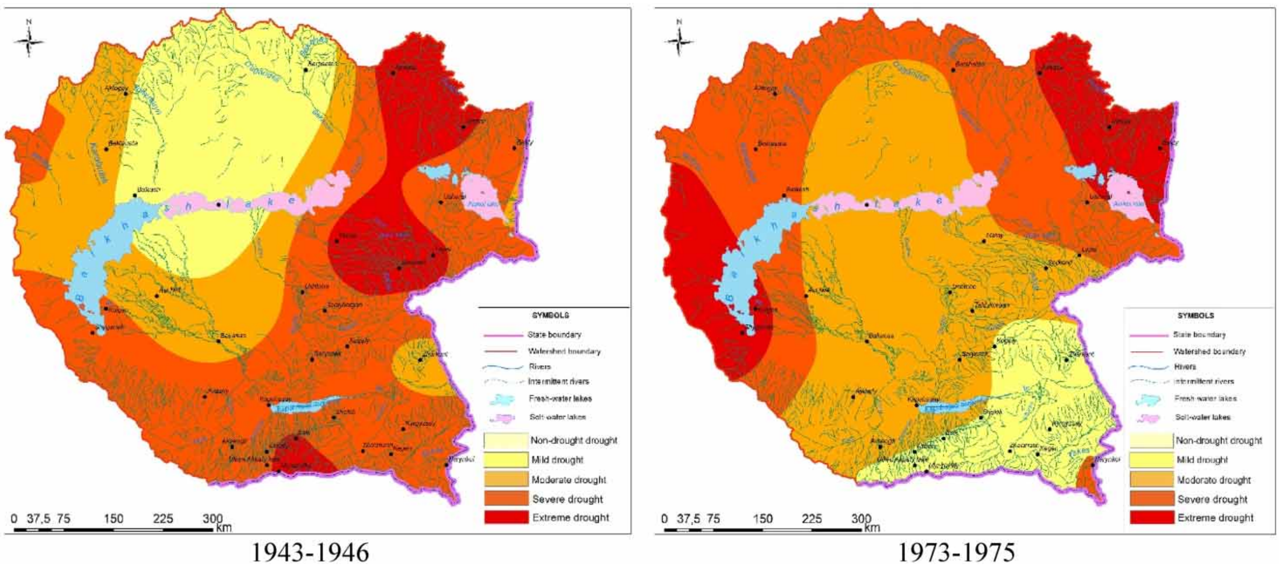

Figure 6 | Spatial distribution of hydrological drought (during previous periods of the lake level decline) according to the SPI in the territory of Ile-Balkhash water economy basin.

Regarding the level of Balkash Lake, hydrological drought clearly has a tendency to influence, since the first critical drop in the water level in the lake occurred in 1946 (Figure 2), which is confirmed by calculations using the SPI drought index in almost all MS of the considered region. From 1944 to 1947 (highlighted in yellow in Table 2), a drought was recorded; its maximum duration at MS Lepsi was 36 months.

The second critical drop in the lake water level was observed in 1987 at the level of 340.65 m BS, the occurrence of hydrological drought during this period is confirmed by calculations using the SPI drought index at the Sarkand and Narynkol MSs (highlighted in green in Table 2), the maximum duration at the Narynkol MS was 141 months. Table 3 shows the parameters of severe hydrological droughts identified by SDI with a time scale of 12 months and with values below −1.0.

The results of Table 3 analysis showed that during the first critical decrease in the lake's water level, the parameters of severe hydrological droughts according to the SDI flow index were identified from 1943 to 1946 with a drought duration from 11 months along Ile River – 37 km to 36 months along Lepsi River – Lepsy (highlighted in yellow in Table 3).

Table 3 | Parameters of severe hydrological droughts identified by SDI with a time scale of 12 months and with values below −1.0

Drought beginning	Drought end	Drought, months	SPI_{min}	Total SPI	SPI_{cp}
Ile River – Kapshagai tract (37 km)					
12/1938	04/1939	4	−1.12	−4.17	−1.04
08/1943	**06/1944**	**11**	**−1.45**	**−13.52**	**−1.23**
09/1970	09/1971	12	−1.71	−18.80	−1.45
07/1972	03/1973	9	−1.37	−11.45	−1.27
03/1976	12/1979	46	−1.65	−59.46	−1.35
04/1983	**07/1987**	**52**	**−1.67**	**−72.26**	**−1.39**
06/1991	08/1993	27	−1.62	−38.90	−1.44
03/1996	09/1996	7	−1.36	−8.83	−1.26
04/2009	10/2009	7	−1.27	−8.27	−1.18
11/2014	14/2016	18	−1.88	−24.71	−1.37
Ile River – 171 km upstream the Kapchagai hydroelectric station					
09/1965	04/1966	9	−1.42	−11.33	−1.26
11/1974	06/1976	20	−2.03	−27.20	−1.43
06/1992	03/1993	10	−1.62	−12.78	−1.28
06/1995	05/1996	12	−1.77	−19.24	−1.60
08/2008	07/2009	12	−1.70	−17.76	−1.48
05/2013	08/2015	28	−2.73	−47.14	−1.68
Ayagoz River – Tarbagatai village					
10/1962	03/1964	18	−1.86	−24.14	−1.34
05/1965	03/1966	11	−1.71	−17.25	−1.57
06/1974	03/1977	34	−2.52	−56.45	−1.66
05/1982	**10/1983**	**18**	**−1.67**	**−25.46**	**−1.41**
05/2008	06/2009	14	−1.27	−14.92	−1.07
Koksu River – Koksu village					
06/1957	06/1958	13	−1.73	−20.58	−1.58
04/1962	05/1963	14	−1.22	−15.19	−1.09
06/1965	05/1966	12	−1.83	−20.86	−1.74
07/1974	10/1976	28	−2.13	−45.94	−1.64
06/1981	11/1984	42	−2.60	−72.96	−1.74
05/1986	**14/1987**	**12**	**−1.53**	**−16.59**	**−1.28**
Lepsi River – Lepsi city					
09/1933	05/1934	9	−2.66	−21.75	−2.42
14/1938	06/1939	15	−2.50	−29.95	−2.00
06/1943	**05/1946**	**36**	**−2.30**	**−61.21**	**−1.70**
07/1957	04/1958	10	−1.54	−14.33	−1.43
04/1983	**04/1984**	**13**	**−1.60**	**−15.71**	**−1.21**
06/1991	08/1992	15	−1.96	−24.04	−1.60
05/1995	06/1996	14	−1.76	−21.83	−1.56
Sharyn River- Sarytogai tract					
09/1962	07/1963	11	−1.43	−13.12	−1.19
06/1976	07/1979	38	−1.76	−55.20	−1.45

(*Continued.*)

Table 3 | Continued

Drought beginning	Drought end	Drought, months	SPI_{min}	Total SPI	SPI_{cp}
11/1982	**05/1985**	**32**	**−1.91**	**−45.04**	**−1.41**
06/1995	05/1996	12	−1.92	−20.10	−1.67
06/2014	05/2015	12	−1.71	−17.57	−1.46
Tekes River – Tekes village					
06/1976	06/1979	37	−2.13	−57.27	−1.55
07/1984	**09/1986**	**27**	**−2.10**	**−43.22**	**−1.60**
07/1995	04/1996	10	−1.41	−12.89	−1.29
09/2014	08/2015	12	−2.00	−18.75	−1.56

It should be noted that, according to the SDI flow index, during the second critical decrease in Balkash Lake water level, the parameters of severe hydrological droughts were identified from 1982 to 1987 with drought duration from 12 months along Koksu River to 52 months along Ile River (highlighted in green in Table 3). In the Ile-Balkhash water economy basin, the average duration of hydrological drought for the period before 1973 was 13 months; for the modern period, the duration of hydrological drought is 22 months.

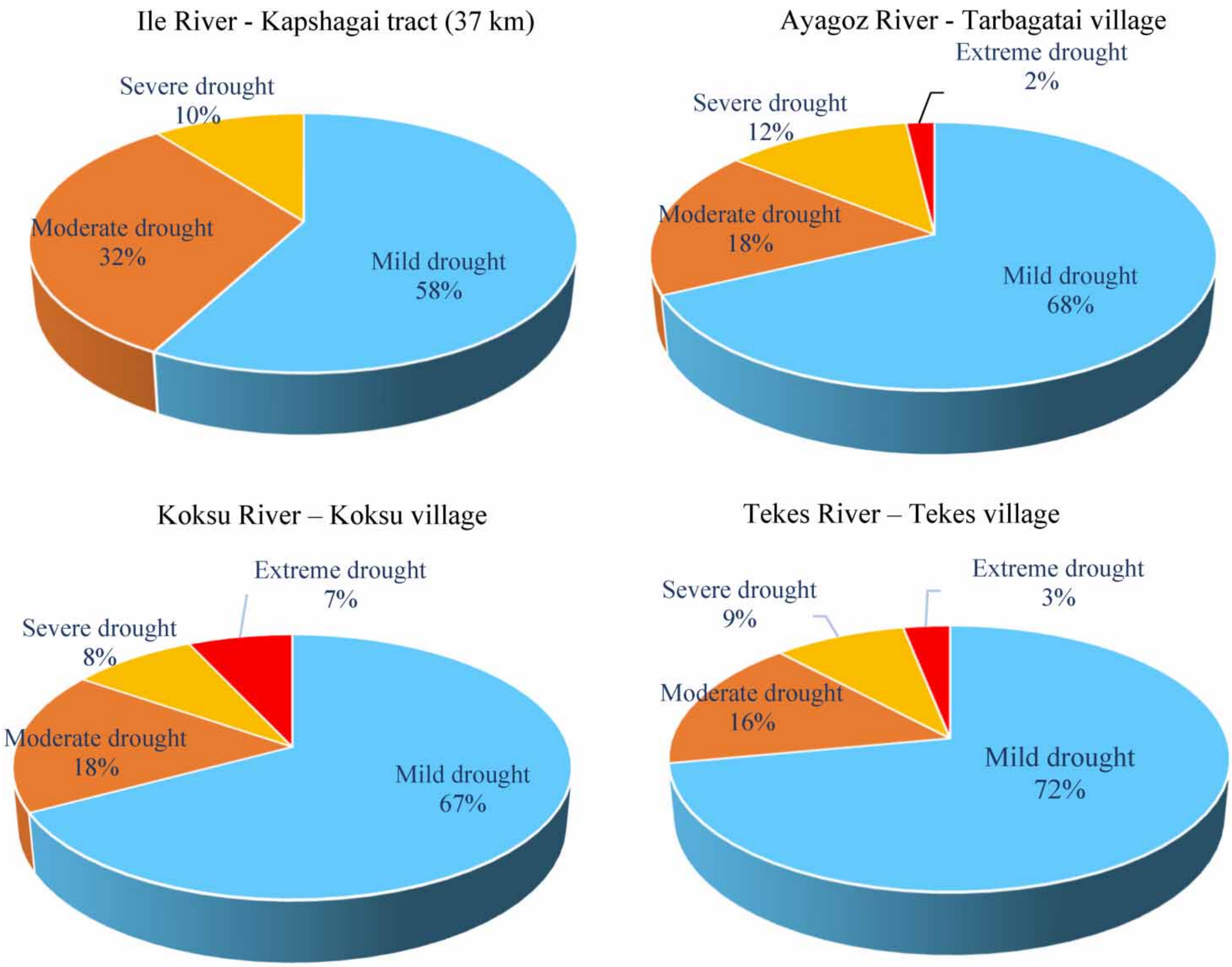

Figure 7 | Frequency of droughts in Ile-Balkhash water economy basin for the period 1961–2020.

Thus, the duration of drought events is an important aspect, since even weak droughts can cause serious problems if they last for several years. The frequency of droughts for the period from 1961 to 2020 is presented in Figure 7.

Analysis of Figure 6 shows that the occurrence of extreme hydrological droughts along the Ayagoz River is 2%, along the Tekes River is 3%, and along the Koksu River is 7%. The frequency of severe hydrological droughts on the main rivers of the considered region varies from 8% to 12%. It appears that with the probability of serious problems associated with hydrological drought, there will be irreversible consequences for the ecological system of Balkhash Lake and the environment, leading to intense water shortage problems. This suggests the requirement to develop strategic plans for water management and to ensure preparedness in drought-subjected areas to combat the increased risk of water scarcity.

CONCLUSIONS

This scientific article conducted a study aimed at assessing hydrological drought using two drought indices: SPI and SDI. The importance of such analysis is considered in the context of hydrological systems for monitoring, forecasting and effective management of water resources. Based on the research results it was concluded that SPI and SDI indices are highly effective in diagnosing and monitoring hydrological drought. It is shown that these indices provide an objective and quantitative assessment of river flow deficit, which is important for the rapid response to drought conditions. The performed analysis has practical importance for planning the sustainable use of water resources, taking measures to adapt to dry periods and ensuring the sustainability of water supply in various sectors of the economy, such as agriculture and industry. Thus, the study results highlight the importance of using SPI and SDI indices to assess hydrological drought, providing valuable information for developing water resource management strategies and mitigating the negative impacts of drought conditions.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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