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Article

Analysis of the Spatiotemporal Variability of Hydrological Drought Regimes in the Lowland Rivers of Kazakhstan

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Abstract: Hydrological droughts occur as a result of various hydrometeorological conditions, such as precipitation deficits, reduced snow cover, and high evapotranspiration. Droughts caused by precipitation deficits and occurring during warm seasons are usually longer in duration. This important observation raises the question that climate change associated with global warming may increase drought conditions. Consequently, it is important to understand changes in the processes leading to dry periods in order to predict potential changes in the future. This study is a scientific analysis of the impact of climate change on drought conditions in the Zhaiyk–Caspian, Tobyl–Torgai, Yesil, and Nura–Sarysu water management basins using the standardized precipitation index (SPI) and streamflow drought index (SDI). The analysis methods include the collection of hydrometeorological data for the entire observation period up to and including 2021 and the calculation of drought indices to assess their intensity and duration. The results of this study indicate an increase in the intensity and frequency of drought periods in the areas under consideration, which is associated with changes in climatic conditions. The identified trends have serious implications for agriculture, ecological balance, and water resources. The conclusions of this scientific study can be useful for the development of climate change adaptation strategies and the sustainable management of natural resources in the regions under consideration.

Keywords: climate; hydrological drought; standardized precipitation index; streamflow drought index

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1. Introduction

Modern climate change is undoubtedly having and will continue to have an impact on climate extremes, including droughts. Droughts are a natural phenomenon associated with moisture deficits; they are observed in different climatic zones and cause enormous damage. According to the UN, drought damage exceeds 20% of the damage [1] caused by all natural disasters. Droughts, especially in their extreme manifestation, have an accelerating effect on the development of desertification, the main cause of which is excessive anthropogenic pressures that increase under conditions of long-term and intensive droughts [2,3].

Drought is a complex phenomenon that can be viewed from several aspects. Central to drought definitions is the concept of moisture deficit. Hydrological drought is characterized by a decrease in water resources (river runoff, reservoirs, etc.) below a certain level. Difficulties in defining drought are related to the need to consider different components of the hydrological cycle, as well as time periods and environments, respectively, when and where moisture deficit occurs. Situations where there is simultaneously a long-term moisture deficit in the soil at great depth and a short-term moisture surplus in the upper layer reflect the difficulties associated with defining and identifying droughts.

There are different approaches used to classify droughts. Depending on the environment in which the signs of moisture deficit are observed, atmospheric and soil droughts are distinguished, and there is also talk about general atmospheric–soil droughts [4,5]. A more detailed classification of droughts, taking into account the types and severity of their effects, is widespread in international literature focused on drought monitoring in regions with high risks of long-term droughts and developed insurance systems [6,7]. Droughts, considered to be manifestations of climatic variability, are divided into meteorological, agricultural, and hydrological droughts. Hydrological droughts are characterized by decrease water flow into rivers and reservoirs, lowering their levels, and a decrease in groundwater storage, leading to difficulties in meeting water demands.

The severity of hydrological droughts is usually determined for catchments or river basins. The specific characteristic of hydrological droughts are their delayed onset compared to meteorological and agricultural droughts, and they can possibly cover larger areas than the area of the causal meteorological drought as regions are linked by hydrological systems [8]. Identifying the relationship between hydrological droughts and precipitation deficits due to climatic causes is often complicated by the combined impact of other factors, such as land-use change and land degradation, on the hydrological characteristics of the basin. Upstream land-use change can modify the hydrological characteristics, such as infiltration rates and surface runoff, resulting in downstream variability in streamflow that increases the possibility of hydrological drought. Land-use change is one of the anthropogenic influences that increases water stress, even if there is no change in the frequency of occurrence of the primary phenomenon: meteorological drought. One classification of droughts that occur in the summer season is provided by [9], as follows:

1. By type of drought: meteorological (atmospheric), soil (agroclimatic), and hydrological
2. By duration of drought: short (duration up to 30 days) and long (more than 30 days)
3. According to the temperature of the environment (air, soil, and water): high and very high. Depending on the environment are considered:
    - Air temperature: high up to 30 °C and very high above 30 °C;
    - Soil temperature: high up to 40 °C and very high above 40 °C;
    - Water temperature: high up to 28 °C and very high above 28 °C.

Following [9], soil drought can be the cause of hydrological drought, which is a continuation of soil–atmospheric drought, leading to the depletion and then drying of the upper groundwater aquifers that feed watercourses. Soil–atmospheric drought causes a reduction in water discharge. Small rivers dry up, medium-sized rivers are fed only by groundwater from deep aquifers during the drought, and in terms of large rivers, the reduction in water discharge depends on the inflow of water from medium-sized rivers, the inflow of water from deep aquifers, and the area of the catchment affected by the drought, the nature of the vegetation, and the characteristics of the climatic zone.

Due to the fact that droughts start with atmospheric drought and then pass to the soil, becoming hydrological droughts, the latter is the final link in the chain of droughts and is an indicator of the greatest depletion of water resources. In some cases, hydrological droughts can occur during low water periods, even with precipitation and sufficient soil moisture, indicating the depletion of aquifers feeding watercourses [10].

Factors forming hydrological drought [11]:

- Hydrogeological: type of water supply of a river or lake, conditions of water occurrence, groundwater supply regime, conditions of underground water supply, and type of hydraulic connection with the river;
- Morphometric: depth of erosion incision of the channel and catchment area;
- Meteorological: air temperature, soil temperature, water evaporation, evaporation from soil, and transpiration by vegetation;

- Anthropogenic water withdrawal for irrigation, water withdrawal by industry, water withdrawal for municipal and domestic needs, and water withdrawal for agricultural needs.

The first three factors are natural in character and exist independently of humans; however, humans, in the course of their economic activities, can still influence this group of factors to a certain extent (e.g., anthropogenic influence on climate). The fourth factor is completely dependent on human activity. This factor is most pronounced in areas of intensive agricultural and industrial development. For lowland river basins, this factor is very significant. The presence of a multitude of facilities related to the use of surface and groundwater leads to the additional depletion of water resources in the catchments of lowland rivers and basins under consideration. Intensive water use may contribute to the depletion of century-old reserves of the deepest groundwater sources, posing a threat relating to the general drying up of the considered territory.

One of the most common approaches to analyzing changes in aridity is based on the use of special indices that, on the one hand, correlate with values reflecting the conditions of agricultural or hydrological drought (soil moisture, runoff) and, on the other hand, can be calculated from available data from standard hydrometeorological observations.

Soil moisture is a key variable in the classification of droughts. Accordingly, soil moisture can be considered primarily an indicator of agricultural drought as it largely controls transpiration and plant growth. At the same time, soil moisture is an indicator of both meteorological and hydrological droughts because it provides an aggregated estimate of the amount of available moisture due to the balance of precipitation, evapotranspiration, and runoff.

The direct use of soil moisture data to assess current climatic changes in global or continental drought conditions is not possible because of the very limited amount of information available. Consequently, special indices based on standard meteorological observations are used to characterize droughts, the values of which allow for the identification of the drought phenomenon and make it possible to assess its severity.

The starting point for all types of droughts is precipitation deficit, which leads to water shortages for different activities, and the values of this meteorological variable are included in one form or another in all drought indices. At the same time, a number of indices rely only on criteria related to the assessment of anomalous precipitation during a selected period of time.

The simplest index is the so-called percentage of normal, i.e., a value equal to the ratio of actual precipitation to the long-term average in percent. This indicator can be evaluated for different time intervals, from one month to one year. One of the disadvantages of this indicator is the significant deviation of precipitation distribution from the normal distribution law in many arid areas. In these areas, the most probable values of precipitation (mode of distribution) may be much lower than the norm (mean value), which complicates the statistical interpretation of the results obtained.

A more sophisticated method used to assess the degree of anomalous precipitation is related to the determination of the probability corresponding to the observed value. A discrete form of this approach, proposed in [12] and called the decile method (decile index), involves dividing an area of rainfall values into equally likely gradations (intervals) and then using the gradation number as the drought index (the lower the number, the greater the degree of drought); this method is implemented by a drought monitoring service in Australia [13,14].

There are various indices for drought monitoring and assessment that can determine the characteristics of drought. The indices are derived from hydrometeorological characteristics (precipitation, air temperature, river flow, soil moisture, etc.) [15].

By the beginning of the 21st century, the standardized precipitation index (SPI) had become the most common aridity index based on precipitation data alone [16–18]. The calculation of the index involves a preliminary analysis of the precipitation distribution function at a selected base interval and its approximation, allowing for the probability of non-exceedance of any observed precipitation value to be determined. The SPI value is an anomaly of the standardized normal distribution; a value of minus 2 or less indicates an extreme error. The SPI can be used to monitor drought conditions over any time interval (from a month to a year or more). The variation of averaging scales makes it possible to monitor, using this index, both the agricultural and hydrological effects of droughts associated with sites with different sensitivities to precipitation deficits.

The SPEI, standardized precipitation and evapotranspiration index, is used as the basis for the SPI but also includes a temperature component; therefore, the index can be used to characterize the effect of temperature on the development of drought through basic water balance calculations. SPEI has an intensity scale on which both positive and negative values are calculated, allowing for the identification of drought and wetting phenomena. This index can be calculated for time periods ranging from 1 to 48 months or longer [19].

The CZI (Z-index), developed in China, is based on the simplicity of calculations when using SPI and improves upon it, further simplifying the calculations. A statistical Z-score is used to identify monitored dry periods. This index is similar to the SPI in that precipitation is used to identify wet and dry periods with the assumption that precipitation obeys a Pearson type III distribution. Monthly time intervals from 1 to 72 months are used in the calculation of the Z-index, which allows for the identification of droughts with different durations [20].

The indices presented are estimated both from observations at meteorological stations and from reanalysis data [21]. Linear and non-linear methods of time series analysis are applied to study the change trend [22,23], which are the main components of the aridity indices fields. The listed indices are statistical in nature, i.e., they are a measure of deviation of current values of the influencing meteorological variables from their distribution on the selected base interval.

Along with statistical indices of aridity, physical–empirical indices are widely spread. The construction of these indices is based on known physical regularities; however, the specific type of such indices and the methods used for their calibration are related to the processing of empirical data, with certain spatial and temporal references. As a consequence, these indices cannot be considered universal and suitable for application at any time intervals. The most common and widely used index of this type in meteorological studies is the Selyaninov hydrothermal coefficient (SHC), proposed in 1928 [24–27]. Conclusions about the probability of occurrence of agricultural droughts of different intensities were based on data from a joint frequency analysis of index values and known drought characteristics. The main drawbacks of the SCC index include the failure to take into account spring moisture reserves in the soil, as well as the use of an indicator that depends on the air temperature to characterize evapotranspiration.

In world practice, the Palmer Drought Severity Index (PDSI), introduced in [28–31], is most commonly used to track changes in drought conditions over long time intervals. The Palmer index is calculated from monthly temperature and precipitation data and information on the water-holding capacity of soils. It considers incoming moisture (precipitation) and soil moisture stores, taking into account potential moisture loss due to temperature effects. For small homogeneous areas, it has been shown [30] that this index is a good indicator of soil moisture, from which regression estimates of moisture content in the upper meter layer of soil can be derived with acceptable accuracy. The main disadvantages of the Palmer index include failure to take into account the influence of snow cover and soil freezing, the use of a simplified scheme of moisture transfer, etc. [32].

The most commonly used index to determine hydrological drought is the SDI drought river flow index. Hydrological droughts are characterized by prolonged (albeit temporary) desiccation of water bodies on the land surface. A more specific type of hydrological drought (apparently the most dangerous) is characterized by a prolonged decrease in river flow. According to the classification of hydrological drought intensity using the “river discharge index” (SDI), these are droughts whose index is less than “minus” 2 [33]. In principle, there are two types of extreme hydrological droughts. The first type are the so-called "seasonal" ("annual") extreme droughts, where runoff remains zero for at least one month each year. The second type are "episodic extreme droughts", when river flow is absent for at least one month during an observation period of 20 years [34].

At present, ongoing climate changes are having significant impacts on changes in the water regimes of rivers. Consequently, extreme hydrological phenomena (hydrological droughts), including the formation of deep low water levels that can cover a vast area, are also associated with changes in climate and river water regimes. There is an increasing need to adapt water management to modern climate change and the conditions of water resources formation [35,36]. The study of hydrological droughts in the territory of the Republic of Kazakhstan is an extremely topical issue and considers several important aspects:

- Water resource deficits (hydrological droughts can significantly reduce water reserves, leading to serious economic and social consequences);
- Under conditions of a changing climate, hydrological anomalies, including droughts, are becoming more pronounced;
- Threat to agriculture (hydrological droughts can lead to reduced crop yields, with negative impacts on food security and human well-being);
- Droughts can cause soil degradation and changes in ecological systems, which directly affect the sustainability of regions;
- Assessment and analysis of hydrological drought characteristics are necessary for effective water resources management and the development of drought prevention and mitigation measures.

2. Materials and Methods

2.1. Description of the Study Area

The Republic of Kazakhstan stretches from west to east for about 3000 km and from north to south for 1800 km. The area of the Republic is more than 2.7 million km^2, with 40% of its territory being deserts and 43% being steppes and semi-deserts. From the east, southeast and south, the republic is framed by mountains; the rest of the area is conventionally considered to be characterized by plains. However, within this territory, there are the mountains and hills of the Kazakh shallow hills, Mugolzhary, and spurs of the Ural Mountains. Here, the rivers are mainly fed by the plains, largely determining their regimes. It is no coincidence that almost all this territory belongs to the distribution area of Kazakh-type rivers, according to the classification of Zaikov [37,38].

The climate of the plain territory is determined by the deep intracontinental position of Kazakhstan, as well as by the character of its surface. Continentality increases as one moves from west to east. The degree of continentality is not constant in time, in summer, it is weakened due to increased zonal circulation. In winter, with stable west–east circulation, thawing occurs across the whole of Kazakhstan. The Kazakhstan plain is open to the unimpeded penetration of air masses. Thus, on the one hand, the relatively simple surface structure favors the consistency of climatic fluctuations over the whole territory under consideration. On the other hand, the large size of the territory inevitably leads to inconsistency.

Four water management basins (WMBs) of the Republic of Kazakhstan (Zhaiyk–Caspian, Tobyl–Torgai, Yesil, and Nura–Sarysu) are considered in this scientific study (Figure 1).

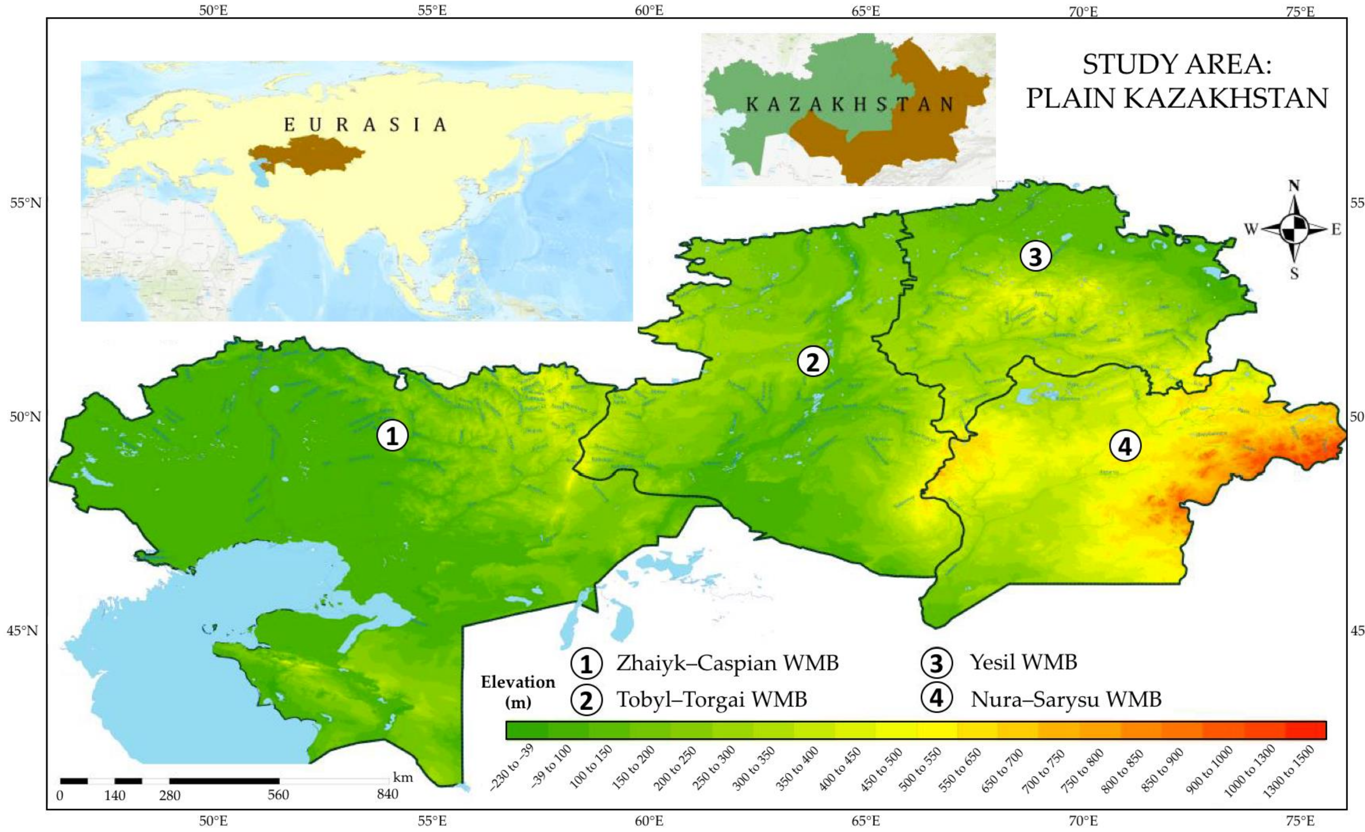


Figure 1. Overview map of the study area.

2.1.1. Zhaiyk–Caspian Water Management Basin

The distribution of the river network within the Zhaiyk–Caspian water management basin is shaped by the presence of the Caspian Sea to the southwest and the mountain formations of the Southern Urals to the northeast. Consequently, the rivers exhibit a general flow direction from northeast to southwest. The basin under study encompasses over a hundred rivers, with twelve exceeding 200 km in length. The Ural River (Zhaiyk) is the basin's primary waterway, boasting a total length of 2534 km. Originating in the Southern Urals within the Russian Federation, the Ural River ultimately flows into the Caspian Sea. Notably, the portion of the river flowing through the Republic of Kazakhstan is 1084 km long.

2.1.2. Tobyl–Torgai Water Management Basin

Aridity and prevalent flat terrain sculpt a unique hydrological landscape within the basin. The river network is restricted primarily to the basin's elevated areas due to this combination of factors. The Tobyl River basin exemplifies this, containing 142 watercourses exceeding 10 km, over half of which are temporary streams under 20 km long. Encompassing both the Tobyl River network and parts of the endorheic Tobyl–Torgai interfluve, the basin exhibits the influence of limited drainage. Similarly, the Torgai River basin showcases a restricted network. Here, the main Torgai River is joined by its right-bank tributary, the Yrgyz, and the Uly-Zhylanshyk River, an internal drainage river that does not reach the central depression. Several smaller rivers with mouths lost within depressions also contribute to the basin's network.

2.1.3. Yesil Water Management Basin

The structure of the hydrographic network is shaped by the basin's topography. Low relief in the east and west, coupled with a general lowering of terrain westward, southward, and partially northward, dictates a central-to-marginal runoff pattern. The main water artery is the Yesil River (left tributary of the Ertis, 2450 km long), with numerous large tributaries like Kalkutan, Zhabai, and Akkanburluk. Notably, the right bank presents a contrasting picture. This flat steppe region exhibits a sparse network of temporary watercourses and ravines, while the left bank boasts significant surface dissection by river valleys and dry ravines, with deeply incised river valleys.

2.1.4. Nura–Sarysu Water Management Basin

The Nura–Sarysu water management basin exhibits a predominantly endorheic drainage pattern. This characteristic manifests in several key features. The Teniz-Korgalzhyn depression within the basin is a collection of terminal lakes lacking any external drainage pathways. Similarly, adjacent basins associated with the Nura, Kulanotpes, and other watercourses all terminate in closed lakes such as Teniz, Korgalzhino, and Kirey. These internal drainage basins underscore the endorheic nature of the system. Notably, even the seemingly independent basin of the Sarysu River ultimately feeds into the endorheic Syrdarya River basin, further reinforcing the concept of internal drainage within the broader region. This unique hydrological signature of the Nura–Sarysu basin plays a critical role in shaping its overall water dynamics and associated ecosystem characteristics.

2.2. Research Materials

In this scientific study, official cadastral materials of RSE “Kazhydromet” were used to analyze the manifestation of hydrological droughts in the plain rivers of the Republic of Kazakhstan. In total, 124 hydrological posts operate in four water management basins, of which, unfortunately, most of them could not be used for calculations due to many omissions in observations or insufficient number of years of observations. To identify hydrological drought using the SDI, water discharge data from hydrological stations with the longest representative observation series and covering retrospective and modern periods were used. Hydrological stations were selected taking into account the minimum number of gaps in observations or those subject to the adequate recovery of missing data. Daily data on water discharge at 45 hydrological posts were used as hydrological information, including the following:

- Seventeen hydrological posts in the Zhaiyk–Caspian WMB;
- Twelve hydrological posts in the Tobyl–Torgai WMB;
- Seven hydrological stations in the Yesil WMB;
- Nine hydrological posts in the Nura–Sarysu WMB.

The number of meteorological stations on the territory under consideration is 126. For hydrological drought calculations using the SPI generator, meteorological stations were selected using the same principle as the hydrological stations: the location of meteorological stations close to hydrological stations. As meteorological information, precipitation data from 46 meteorological stations were used, including the following:

- Eighteen meteorological stations in the Zhaiyk–Caspian WMB;
- Eleven meteorological stations in the Tobyl–Torgai WMB;
- Seven meteorological stations in the Yesil WMB;
- Ten meteorological stations in the Nura–Sarysu WMB.

The spatial and temporal distributions of drought in the considered territory of four water management basins were analyzed from the beginning of instrumental observations up to and including 2021.

The names of the meteorological stations by WMB used for calculations are presented in Table 1. The names and characteristics of the hydrological posts by WMB are shown in Table 2. The location of hydrological posts and meteorological stations by WMB used for calculations is shown in Figure 2.

Table 1. Names of meteorological stations by WMB used for calculations.

Zhaiyk–Caspian WMB							
1	Uralsk	6	Dzhambeyty	11	Rodnikovka	15	Emba
2	Makhambet	7	Shyngarlau	12	Aktobe	16	Mugodzharskaya
3	Kamenka	8	Uil	13	Kosistek	17	Shalkar
4	Kaztalovka	9	Karaulkeldy	14	Novorossiyskoe	18	Ayakkum
5	Zhalpaktal	10	Il′insky				
Tobyl–Torgai WMB							
1	Tobol	4	Kushmurun	7	Amangeldy	10	Karabutak
2	Jetygara	5	Arkalyk	8	Kulzhambay	11	Komsomolskoye
3	Arshalinsky	6	Ekidyn	9	Irgiz		
Yesil WMB							
1	Arshaly	3	Akkol	5	Balkashino	7	Ereimentau
2	Astana	4	Atbasar	6	Ruzaevka		
Nura–Sarysu WMB							
1	Rodnikovskiy	4	Bes-Oba	7	ZhanaArka	9	Zhezkazgan
2	Korneevka	5	Aksu-Ayuly	8	Kyzyltau	10	Zliha
3	Karagandy	6	Zharyk				

Table 2. The names and characteristics of the hydrological posts by WMB used for calculations.

N°	Hydrological Station	Distance from the River Mouth (km)	Watershed Area (km^2)	Average Height of the Basin, (m)	Runoff Observation Period	Number of Years of Observation
			Zhaiyk–Caspian WMB			
1	Zhaiyk-Kushum	732	190,000		1912–1918, 1920–2021	109
2	Zhaiyk-Makhambet	145	230,000		1936–1941, 1943–2021	85
3	Or-Bogetsay	208	7480	350	1958–1997, 2000–2021	62
4	Elek-Shelek	112	37,300	250	1949–2006, 2008–2021	72
5	Kargaly-Karagala	7	5000	370	1957–2001, 2003–2021	64
6	Kosistek-Kosistek	24	281	430	1957–2021	65
7	Ulken Kobda-Kobda	172	8110	240	1961–2021	61
8	Shyngyrlau-Kentubek	87	4660	130	1954–2000, 2005–2006, 2011–2021	60
9	Shagan-Kamenny	116	4000	130	1931–1941, 1948, 1950–2010	73
10	Derkul-Beles	54	1820	101	1963–1988, 1990–1995, 1997, 1998, 2002–2007, 2009–2021	52
11	Karaozen-Zhalpaktal	178	13,200		1981, 1982, 1984–1991, 1994–1998, 2000–2002, 2004–2005, 2008–2015, 2017–2021	32
12	Saryozen-Bostandyk	205	11,000		1975–1978, 1980–1992, 1994, 2008–2009, 2011–2021	
13	Oiyl-Oiyl	420	17,100		1981, 1984–2021	39
14	Temir-Sagashili	166	960	303	1968–2021	54
15	Sagyz-Sagyz	348		160	1954–1978, 1980–1992	38
16	Olenty-Zhympity	127	1290	80	1964–1997, 2007, 2009–2021	48
17	Kopyrankaty-Algabas	5	723	80	1957–1998, 2000–2004, 2006–2021	53

Table 2. *Cont.*

N°	Hydrological Station	Distance from the River Mouth (km)	Watershed Area (km^2)	Average Height of the Basin, (m)	Runoff Observation Period	Number of Years of Observation
Tobyl–Torgai WMB						
1	Tobyl-Akkarga	1549	2820	324	1959–1967, 1969, 1974–1976, 1978–1991, 2004, 2006–2008, 2010–2018	40
2	Tobyl-Grishenka	1399	13,400	320	1937–1997, 1999–2021	84
3	Tobyl-Kostanay	1185	44,800	268	1931–1997, 1999–2021	90
4	Ayat-Varvaryinka	85	10,300	285	1952–1997, 1999–2021	69
5	Togyzak-Togyzak	70	7970	269	1936, 1940–1997, 2004–2021	77
6	Obagan-Aksuat	102	22,300	178	1938–1944, 1958–1961, 2003–2005, 2007, 2012–2021	25
7	Torgay-Tusum Sands	474	56,500	228	1940–1981,1983–1995, 1999–2006, 2010–2021	75
8	Karatorgay-Urpek	29	15,000	366	1941–1944, 1947–1990, 1992, 1993, 1995, 2001–2005, 2010–2021	67
9	Sarytorgay-Sarytorgay	3	5870	400	1960–1980, 1982–1984, 1986, 1987, 2009–2021	39
10	Yrgyz-Shenbertal	229	26,800	270	1961–1996, 2005, 2006, 2009–2021	51
11	Damdy-Damdy	65	1850		1955, 1956, 1959–1963, 2010–2021	19
12	Uly Zhylanshyk-Korgantas	397	170	645	1958–1986	29
Yesil WMB						
1	Yesil-Turgen	2367	3240	524	1974–2021	48
2	Moiyldy-Nikolayevka	22	472	530	1973–1995, 2001–2021	49
3	Kalkutan-Kalkutan	44	16,500	361	1937–1940, 1955, 1956, 1958–2021	70
4	Zhabay-Atbasar	16	8530	364	1936–1940, 1944, 1945, 1947–2021	82
5	Akkanburlyk-Vozvyshenka	12	6250	315	1938–40, 1951–1990, 2003–2021	62
6	Imanburlyk-Sokolovka	29,9	4070	282	1950–2021	72
7	Silety-Izobilnoye	134	14,600	340	1959–1965, 1968–2021	61
Nura–Sarysu WMB						
1	Nura-Besoba	894	1050	900	1960–2006, 2011–2021	58
2	Nura-Sheshenkara	785	13,980	719	1960–2021	62
3	Nura-Balykty	705	17,960	690	1960–2021	62
4	Nura-Koshkarbayeva	369	50,760	606	1960–2015, 2017–2021	62
5	Sherubainura-Karamuryn	102	8700	790	1960–2021	62
6	Con-Birlik	38	10,300	450	1950–1955, 1957–1966, 1968–1991, 1996, 2001–2005, 2007	47
7	Kulanotpes-Sherbakovsky	124	4530	493	1962–1965, 1967–1997	35
8	Sarysu-189th passage	698	26,900	635	1962–1997, 2000–2021	58
9	Zhamansarysu-Atasu	2.5	9200	711	1932–1997, 2009–2021	57

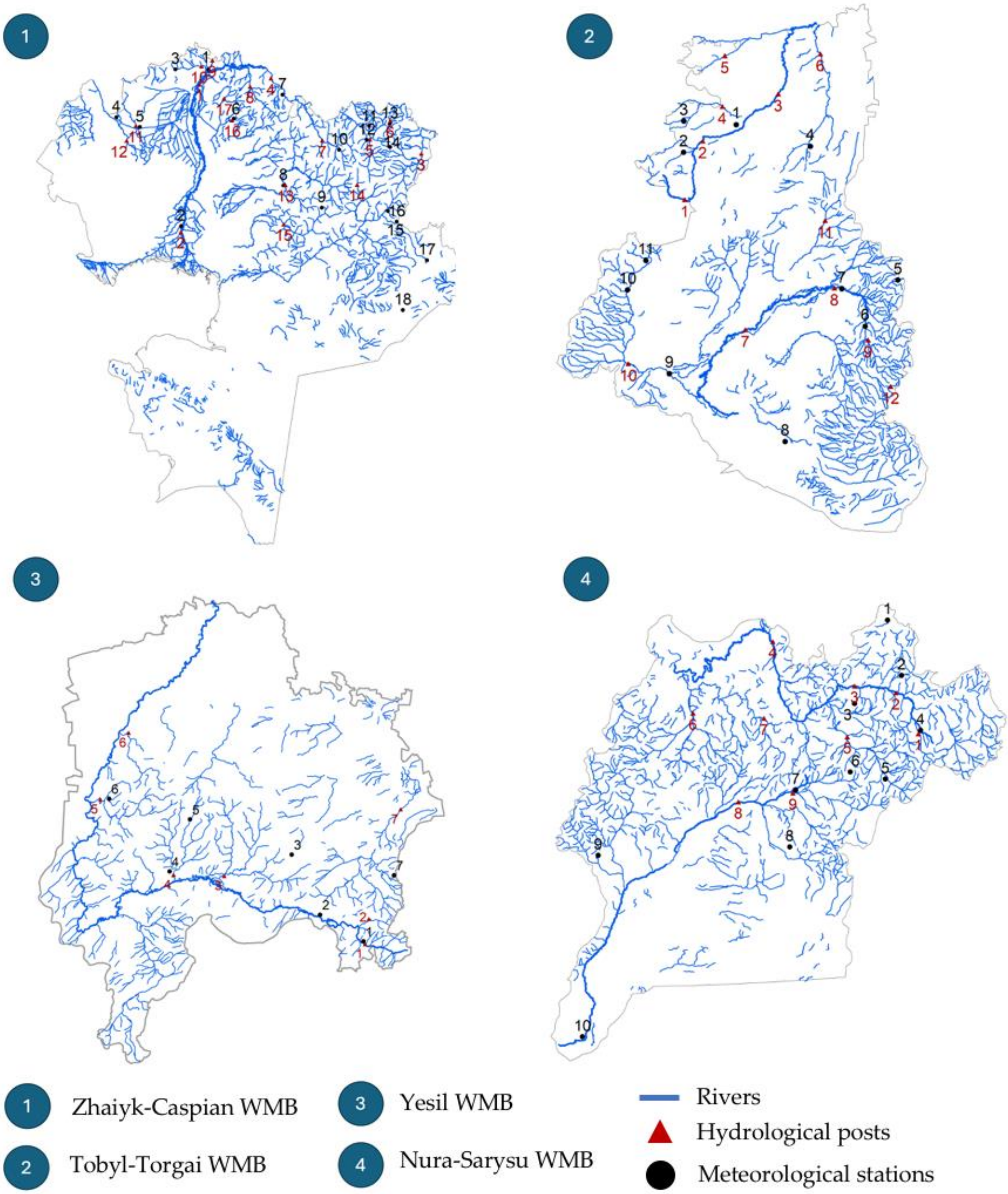


Figure 2. Schematic map of the location of hydrological posts and meteorological stations following the numbering shown in Tables 1 and 2.

2.3. Research Methods

In this work, two quantitative drought indicators were used to identify meteorological and hydrological droughts: the standardized precipitation index (SPI) calculated using the SPI Generator software developed at the National Drought Mitigation Centre, University of Nebraska-Lincoln, USA [39] and the standardized drought index (SDI) calculated using the DrinC software developed at the Centre for the Assessment of Natural Hazards and Proactive Planning & Laboratory of Reclamation Works and Water Resources Management of the National Technical University of Athens, Greece [40].

In this work, groups with extremely low water availability were defined using modular coefficients that corresponded to a certain water availability, according to the Code of Rules 33-101-2003 [41]. For observation periods, ranging from 15 to 30 years, three groups of years are distinguished: high-water years ($P < 33.3\%$), medium-water years ($33.3\% \leq P \leq 66.7\%$), and low-water years ($P > 66.7\%$). When the duration of observations exceeds 30 years, five groups are distinguished: very high-water years ($P < 16.7\%$), high-water years ($16.7\% \leq P < 33.3\%$), medium-water years ($33.3\% \leq P \leq 66.7\%$), low-water years ($66.7\% < P \leq 83.3\%$), and very low-water years ($P > 83.3\%$). Modular coefficients for two periods were calculated to identify low-water groups along the supply curve. The average annual discharge for hydrological stations of the territory under consideration was used for calculations.

To assess temporal variability based on the studies of previous years, it was decided to divide the time series for the tipping year into two periods, before 1973 and after 1974, since for the territory under consideration, 1973–1974 is considered to violate the stationarity of the runoff series [42,43]. The average annual discharges of all hydrological stations were used for the calculations.

The threshold method [44,45] was used to investigate runoff deficit, where it is important to determine the beginning and end of a drought. It is based on the determination of a threshold value of minimum discharge (long-term average) below which a period of low flow is observed. The choice of the threshold value is dictated by considerations of different water management needs and is consistent with the type of water regime of the river. To characterize hydrological droughts in permanent watercourses, the threshold may be chosen among quantiles of 70–90% probability of exceedance; for drying rivers that have flows only after significant precipitation, flows with a 20% probability of exceedance would not be unreasonably high thresholds [46].

The main design characteristics are the duration of the deficit period, deficit depth (total deficit), and deficit intensity (ratio of deficit depth to duration). If the study is conducted for rivers with a long continuous interflow, these characteristics take the form of annual values [47,48]. The set of such annual characteristics form a series of extreme values that can be subjected to standard statistical treatments. In this scientific study, the analysis was carried out for 50 hydrological posts based on the available series of monthly mean discharge. To determine the threshold values, an absolute curve of water discharge duration was constructed, from which discharge values of the corresponding availability were taken.

Further, yearly and monthly periods marked below 90% water availability were analyzed—deficit and above 10%—indicating an extreme increase in water availability. Then, these volumes of water deficit or surplus were determined for these periods. This work also considered an integral indicator of "severity", which is the ratio of deficit or surplus to the duration of the phenomenon. Two quantitative drought indicators were used to identify meteorological and hydrological droughts: the standardized precipitation index (SPI) and the streamflow drought index (SDI) [33]. The standardized precipitation index uses the rigorous apparatus of mathematical statistics to estimate a drought using retrospective and current rainfall data. This method is based on the assumption that precipitation follows a gamma distribution. The algorithm used to calculate the SPI according to [17] is as follows:

- A gamma distribution function with the following form is constructed from the precipitation sums data:

$$f_{\alpha,\beta} = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta}, x > 0 \tag{1}$$

where α and β are positive shape and scale parameters, $x > 0$ is the amount of precipitation, and $G(\alpha)$ is the Euler gamma function; the parameters of this function are determined for each weather station with the selected time resolution;

- The cumulative probability function of a standard normally distributed random variable is constructed on the basis of the distribution density;
- Using the obtained normal distribution, the sums of precipitation are reduced to the form of SPI. A classification of drought conditions is shown in Table 3.

Table 3. Classification of drought conditions according to the SPI.

SPI Value Intervals	Characterization of the Dryness Category of the Territory
2.0+	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
−0.99 to 0.99	Near normal
−1.0 to −1.49	Moderately dry
−1.5 to −1.99	Severely dry
−2 and less	Extremely dry

According to [49], a drought occurs whenever the SPI falls to −1 and below. A drought ends when the SPI value reaches positive values. Different natural components respond differently to precipitation anomalies:

- Soil moisture changes respond to precipitation anomalies on a short-term scale;
- Groundwater and river flow conditions reflect long-term precipitation anomalies.

Consequently, precipitation accumulations at the following scales are used to determine the onset of different types of droughts:

- One–two months for meteorological drought;
- One–six months for agricultural drought;
- Six–twenty-four months and more for hydrological drought.

A 9-month SPI links seasonal drought to long-term droughts that may become hydrological droughts, while a 12-month or greater SPI is associated with significant decreases in river flows, reservoir levels, and groundwater levels.

The SDI drought river flow index uses the same methodology as that used to calculate the standardized precipitation index. The streamflow index is calculated for the hydrological year beginning in October and ending in September (river discharge volume is used). Negative values of the SDI are assessed as a dry period (Table 4).

Table 4. SDI values for drought severity classification.

Index Value	Description
$\mathrm{SDI} \geq 2$	Extremely Wet
$2 \geq \mathrm{SDI} \geq 1.5$	Very Wet
$1.5 \geq \mathrm{SDI} \geq 1$	Moderately Wet
$1 \geq \mathrm{SDI} \geq -1$	Near Normal
$-1 \geq \mathrm{SDI} \geq -1.5$	Moderately Dry
$-1.5 \geq \mathrm{SDI} \geq -2$	Severe Dry
$\mathrm{SDI} \leq -2$	Extremely Dry

3. Results

The main sign of the onset of hydrological drought is the cessation of runoff or a sharp drop in the water level in a watercourse or reservoir; hydrological drought is fixed at a steady decrease of 50% of the long-term average value of water flow in a river. The most reasonable natural factor contributing to the increase in the runoff of plain rivers is atmospheric precipitation.

Changes in mean annual water discharge of plain rivers are largely synchronized and depend on changes in precipitation, which confirms the hypothesis of controllability of water availability of the studied objects by external factors, namely, natural factors. Consequently, the most reasonable natural factor contributing to the increase in water flow in water bodies is atmospheric precipitation.

The most informative indicators for drought diagnostics are SPI indices calculated using monthly precipitation totals. Negative SPI values signal the onset of hydrological droughts of different severities, and in most cases, they correspond to the low-water cycles of the rivers of the territory under consideration.

The SPI Generator Application makes it possible to detect these droughts and identify their parameters. To diagnose the beginning, end, and severity of droughts, monthly data were used, which were obtained by accumulating precipitation at 9-, 12-, and 24-month scales. The results of the parameters of extreme hydrological droughts identified using SPI with a time scale of 12 months on the −2 index are presented in Table 5.

Table 5. The parameters of hydrological drought extremes identified via SPI with a time scale of 12 months by index −2.

Meteorological Station	Drought Initial Date	Drought End Date	Duration of Drought, Months	SPI Minimum	SPI Accumulated	SPI Average
Zhaiyk–Caspian water management basin						
Ural'sk	July 1943	September 1945	26	−2.08	−25.37	−0.98
	October 1949	September 1956	83	−3.02	−115.71	−1.39
	November 1975	October 1976	11	−2.12	−16.34	−1.49
Makhambet	January 1977	October 1979	33	−2.08	−25.06	−0.76
Kamenka	June 1972	August 1973	14	−2.53	−22.82	−1.63
	June 1975	September 1976	15	−3.3	−31.62	−2.11
Zhalpaktal	August 1929	May 1931	21	−2.68	−28.47	−1.36
	August 1937	May 1941	45	−2.78	−56.87	−1.26
	December 1944	September 1945	9	−2.75	−14.43	−1.6
	January 1949	June 1952	41	−2.83	−67.92	−1.66
	October 1955	July 1956	9	−2.92	−14.93	−1.66
	March 1976	December 1977	21	−2.07	−16.79	−0.8
Kaztalovka	November 1975	August 1976	9	−2.04	−13.04	−1.45
	April 1999	September 2000	17	−2.01	−20.46	−1.2
	April 2003	July 2008	63	−2.54	−67.18	−1.07
Shyngyrlau	November 1939	November 1940	12	−2.43	−22.29	−1.86
	August 1951	August 1954	36	−2.32	−36.87	−1.02
	September /2014	April 2016	19	−4.02	−44.61	−2.35
Dzhambeity	June 1936	November 1940	53	−2.42	−73.11	−1.38
	April 1950	September 1953	41	−2.83	−41.51	−1.01
	October 1955	October 1956	12	−2.78	−20.74	−1.73
	March 2015	April 2016	13	−2.5	−22.67	−1.74
Aktobe	June 1930	September 1932	27	−2.37	−28.5	−1.06
	September 1933	July 1941	94	−3.27	−140.96	−1.5
	April 1950	September 1956	77	−2.83	−90.66	−1.18
	August 1975	October 1976	14	−2.05	−11.75	−0.84
Novorossiyskoye	June 1930	August 1931	14	−2.99	−18.76	−1.34
	October 1932	August 1941	106	−3.46	−212.42	−2
	August 1944	September 1945	13	−2.71	−25.78	−1.98

Table 5. *Cont.*

Meteorological Station	Drought Initial Date	Drought End Date	Duration of Drought, Months	SPI Minimum	SPI Accumulated	SPI Average
Kosistek	August 1965	June 1966	9	−2.28	−9.34	−1.04
	August 1975	December 1977	28	−2.68	−31.43	−1.12
	August 2010	August 2011	12	−2.01	−14.26	−1.19
	November 2012	September 2013	10	−2.1	−14.56	−1.46
	March 2015	February 2016	11	−2.11	−8.84	−0.8
	June 2019	July 2020	13	−2.09	−15.43	−1.19
Rodnikovka	December 1939	April 1941	16	−2.61	−25.66	−1.6
	April 1944	August 1945	16	−3.71	−41.28	−2.58
	May 1950	December 1953	43	−2.72	−48.48	−1.13
	September 1975	July 1976	10	−2.3	−8.87	−0.89
	August 2010	September 2011	13	−2.03	−15.71	−1.21
	November 2012	September 2013	10	−2.25	−15.87	−1.59
	February 2015	March 2016	13	−2.48	−18.12	−1.39
Il’insky	September 1975	July 1976	10	−2.68	−14.92	−1.49
	September 2012	September 2013	12	−2.53	−20.65	−1.72
Emba	July 1929	July 1931	24	−2.44	−28.74	−1.2
	July 1933	November 1937	52	−2.59	−78.96	−1.52
	September 1944	December 1945	15	−2.49	−22.27	−1.48
	September 1951	May 1953	20	−2.15	−18.25	−0.91
Mugodzharskaya	June 1936	March 1940	45	−2.62	−64.81	−1.44
	January 1949	September 1950	20	−3.01	−25.91	−1.3
	August 1951	October 1953	26	−3.47	−44.61	−1.72
	January 2019	January 2020	12	−2.05	−13.92	−1.16
Karaulkeldy	July 1939	May 1941	22	−2.18	−23.49	−1.07
	March 1949	May 1953	50	−3.37	−65.87	−1.32
	October 1955	October 1956	12	−2.17	−11.22	−0.94
	June 1975	July 1978	37	−2.82	−43.97	−1.19
Uil	December 1935	August 1941	68	−3.1	−123.35	−1.81
	September 1951	September 1952	12	−2.16	−9.02	−0.75
	October 1955	July 1956	9	−2.17	−9.84	−1.09
	August 1975	September 1976	13	−2.66	−17.08	−1.31
Shalkar	April 1944	March 1946	23	−3.3	−41.34	−1.8
	June 1951	June 1952	12	−2.75	−19.47	−1.62
	April 1955	June 1956	14	−2.87	−30.88	−2.21
	June 1957	April 1958	10	−2.17	−11.87	−1.19
Ayakkum	December 1950	September 1952	21	−2.77	−36.46	−1.74
	October 1996	April 1997	6	−2.2	−9.18	−1.53
Tobyl–Torgai water management basin						
Dzhetygara	January 1952	May 1956	52	−2.31	−53.73	−1.03
	August 1961	September 1963	25	−2.33	−36.38	−1.46
	November 1975	November 1976	12	−2.08	−11.42	−0.95
Arshalinsky	June 1973	July 1974	13	−2.19	−9.92	−0.76
	August 1975	December 1977	28	−3.04	−40.99	−1.46
	April 2009	November 2010	19	−2.16	−19.2	−1.01
Tobol	December 1951	June 1953	18	−2.65	−25.86	−1.44
	July 1955	May 1956	10	−2.52	−21.93	−2.19
	July 1995	May 1999	46	−2.86	−80.96	−1.76
Arkalyk	September 1955	January 1958	28	−2.78	−37.77	−1.35
	September 1975	June 1976	9	−2.05	−7.23	−0.8
Amangeldy	September 1975	October 1976	13	−2.24	−12.53	−0.96

Table 5. *Cont.*

Meteorological Station	Drought Initial Date	Drought End Date	Duration of Drought, Months	SPI Minimum	SPI Accumulated	SPI Average
Ekidyn	August 1975	May 1978	33	−2.61	−41	−1.24
	December 1993	November 1994	11	−2.28	−11.29	−1.03
	August 2006	August 2007	12	−2.71	−15.82	−1.32
Irgiz	August 1927	June 1928	10	−2.13	−12.1	−1.21
	April 1944	December 1945	20	−3.65	−40.84	−2.04
	November 1991	October 1992	11	−2.08	−10.4	−0.95
Komsomolskoye	July 1975	April 1978	33	−3.01	−34.91	−1.06
	May 1996	November 1997	18	−2.13	−17.9	−0.99
Karabutak	September 1951	May 1953	20	−2.01	−16.71	−0.84
	August 1955	May 1956	9	−2.66	−17.3	−1.92
	July 1975	October 1979	51	−2.9	−71.37	−1.4
Kulzhambai	March 1996	March 1997	12	−2.28	−16.74	−1.4
	January 2006	January 2008	24	−2.89	−29.36	−1.22
Kushmurun	June 1945	July 1946	13	−2.58	−16.5	−1.27
	March 1949	July 1950	16	−2.78	−19.82	−1.24
	September 1951	August 1953	23	−2.23	−35.67	−1.55
	July 1998	June 1999	11	−2.03	−15.58	−1.42
Yesil water management basin						
Arshaly	June 1977	May 1978	11	−2.09	−9.33	−0.85
	November 1991	August 1992	9	−2.17	−14.05	−1.56
	January 1998	May 2000	28	−2.31	−34.77	−1.24
	August 2006	June 2007	10	−2.01	−10.73	−1.07
Astana	December 1950	July 1953	31	−3.97	−71.65	−2.31
	August 1955	April 1958	32	−3.62	−43.67	−1.36
	June 1982	May 1983	11	−2.17	−9.15	−0.83
Akkol	July 1935	September 1939	50	−3.23	−89.9	−1.8
	September 1940	October 1941	13	−2.32	−21.3	−1.64
	July 1952	May 1954	22	−2.26	−14.4	−0.65
	October 1955	March 1957	17	−2.1	−15.56	−0.92
	January 1998	February 2000	25	−2.29	−22.77	−0.91
Balkashino	September 1936	August 1941	59	−2.22	−57.68	−0.98
	September 1951	July 1953	22	−2.71	−37.11	−1.69
Atbasar	June 1937	October 1938	16	−2.24	−24.28	−1.52
	May 1949	July 1953	50	−3.27	−89.33	−1.79
	June 1955	May 1958	35	−3.03	−51.59	−1.47
	October 1968	July 1969	9	−2.15	−17.2	−1.91
Ruzayevka	April 1937	August 1938	16	−2.78	−30.58	−1.91
	August 1948	August 1950	24	−2.48	−32.51	−1.35
	September 1951	June 1953	21	−2.22	−24.85	−1.18
	July 1965	July 1966	12	−2.88	−25.85	−2.15
	July 1975	August 1977	25	−2.63	−33.04	−1.32
Ereimentau	December 1955	July 1958	31	−2.7	−38.63	−1.25
	August 1965	June 1966	10	−2.11	−10.54	−1.05
	May 1998	June 1999	13	−2.64	−18.79	−1.45
	November 2010	October 2011	11	−2.64	−17.68	−1.61
Nura–Sarysu water management basin						
Bes-Oba	August 1944	August 1946	24	−2.03	−27	−1.12
	April 2012	July 2016	51	−2.03	−41.93	−0.82

Table 5. *Cont.*

Meteorological Station	Drought Initial Date	Drought End Date	Duration of Drought, Months	SPI Minimum	SPI Accumulated	SPI Average
Karagandy	August 1944	August 1946	24	−2.29	−43.39	−1.81
	October 1950	February 1954	40	−3.52	−62.49	−1.56
	October 1955	December 1957	26	−2.17	−31.04	−1.19
Aksu-Ayuly	January 1951	December 1953	35	−2.61	−44.07	−1.26
	August 1955	May 1958	33	−2.5	−42.32	−1.28
Korneevka	August 1974	June 1978	46	−2.7	−56.49	−1.23
	September 1997	July 1998	10	−2.41	−16.72	−1.67
	May 1999	May 2000	12	−2.73	−8.53	−0.71
	July 2003	April 2004	9	−2	−8.82	−0.98
Rodnikovsky	July 1997	June 1999	23	−3.54	−46.9	−2.04
Zharyk	December 1936	March 1938	15	−2.82	−33	−2.2
	March 1939	June 1947	99	−3.47	−153.35	−1.55
	November 1950	January 1954	38	−2.87	−51.47	−1.35
	August 1955	March 1958	31	−2.39	−49.51	−1.6
Zhana Arka	July 1940	February 1942	19	−2.16	−25.71	−1.35
	January 1945	May 1947	28	−2.52	−25.69	−0.92
	May 1951	September 1952	16	−3.39	−35.26	−2.2
	September 1955	April 1958	31	−2.45	−44.53	−1.44
	December 1991	September 1992	9	−2.18	−10.61	−1.18
Zhezkazgan	March 1939	February 1940	11	−2.13	−7.78	−0.71
	April 1944	January 1946	21	−3.32	−54.53	−2.6
	January 1951	June 1953	29	−2.92	−49.64	−1.71
Zlikha	May 1957	April 1958	11	−2.21	−12.89	−1.17
	November 1995	April 1999	41	−3.28	−65.94	−1.61
Kyzyltau	July 1950	June 1952	23	−3.02	−49.91	−2.17
	December 1998	September 2001	33	−3	−60.2	−1.82

a. Zhaiyk–Caspian water management basin

The analysis presented in Table 3 shows that, in the considered water management basin, the duration of hydrological drought varies widely, from 106 (MS Novorossiyskoye, period 1932–1941) to 6 months (MS Ayakkum, period 1996–1997). The longest hydrological droughts were observed in the 1930s—MS Aktobe (duration 94 months; period 1933–1941), MS Dzhambeity (duration 53 months; period 1936–1940), MS Emba (duration 52 months; period 1933–1937), and MS Zhalpaktal (duration 45 months; period 1937–1941). It should be noted that the multi-year course of river flow in a significant part of Kazakhstan has very characteristic features: the exceptional low-water years of the 1930s (fortunately, having no analog in the subsequent time) and very high-water years (though, at the expense of individual years) of the 1940s.

The lowest SPI value is −4.02 (MS Shyngyrlau; period 2014–2016, lasting 19 months). In the modern period, a major hydrological drought in the considered water basin was recorded in the period 2003–2008, lasting 63 months at the Kaztalovka MS.

b. Tobyl–Torgai water management basin

The longest hydrological droughts in this water basin were observed on the Dzhetygara MS (duration 52 months; period 1952–1956) on the Karabutak MS (duration 51 months; period 1975–1979). The lowest SPI value is −3.65 (Yrgiz MS; period 1944–1945, duration 20 months); in the modern period, the lowest SPI value is −2.89 (Kulzhambay MS; period 2006–2008, duration 24 months). Regarding the 1950s, it should be noted that hydrological drought was observed practically over the whole territory of the water basin—MS Tobol, MS Arkalyk, MS Karabutak, and MS Kushmurun. Analysis of the obtained results shows the following picture: hydrological drought was recorded in 1950, 1970, 1990, 2000, and 2010, and it should be noted that, in the modern period, there has been a reduction in the intervals between droughts; earlier, they occurred approximately every 20 years, and now, this interval has been reduced to 10 years.

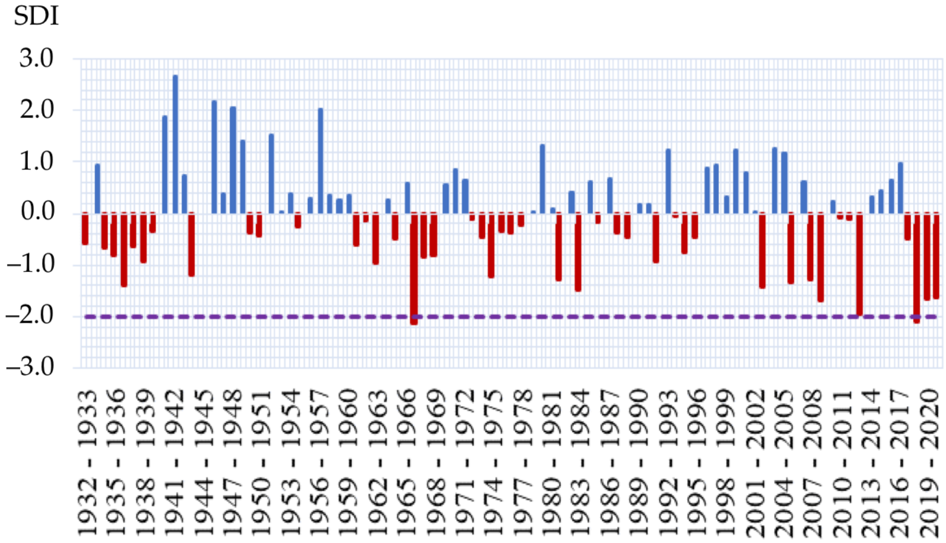
c. Yesil water management basin

In the Yesil water basin, the longest hydrological droughts were observed at the following meteorological stations: MS Balkashino, with a duration of 63 months from 1936 to 1941; MS Astana, with a duration of 50 months from 1935 to 1939; and MS Atbasar, with a duration of 50 months from 1949 to 1953. The lowest SPI value is −3.97 (MS Astana; period 1950–1953, duration 31 months). In the modern period, a major hydrological drought in the considered water basin was recorded at MS Arshaly in 1998–2000, lasting 28 months.

d. Nura–Sarysu water management basin

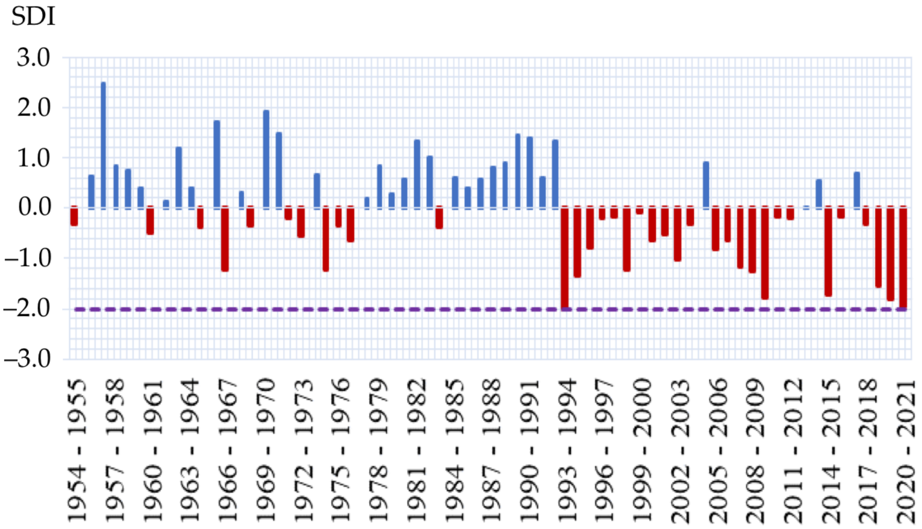
In this water basin, the longest hydrological droughts were observed at the following meteorological stations: MS Zharyk, with a duration of 99 months from 1939 to 1947; MS Bes-Oba, with a duration of 51 months from 2012 to 2016; MS Korneevka, lasting 46 months from 1974 to 1978; MS Zlikha, lasting 41 months from 1995 to 1999; and MS Karaganda, lasting 40 months from 1950 to 1954. The lowest SPI value is −3.54 (MS Rodnikovsky; period 1997–1999, lasting 23 months). In the modern period, a major hydrological drought in the considered water basin was recorded at MS Bes-Oba in the period 2012–2016, with a duration of 51 months.

Based on the results of the calculations, graphs showing the dynamics of dry and wet periods for hydrological drought by SDI were constructed. The SDI was implemented for each hydrological post with all considered time steps (12-month). All index values are based on a comparison for a specific period with the runoff volume of the same period for all years included in the analysis. In the graphs, positive values indicate above-average runoff volume and negative values indicate below-average runoff volume. Figures 3–6 show examples of graph realizations for the SDI for the rivers of the considered water management basins.

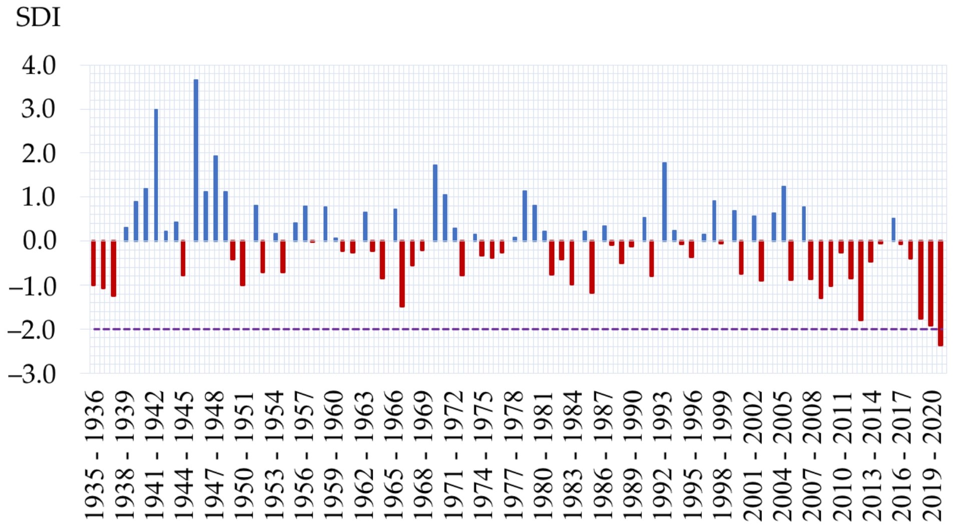


(**a**) Or-Bogetsay

Figure 3. *Cont.*



(**b**) Shyngyrlau–Grigorievka

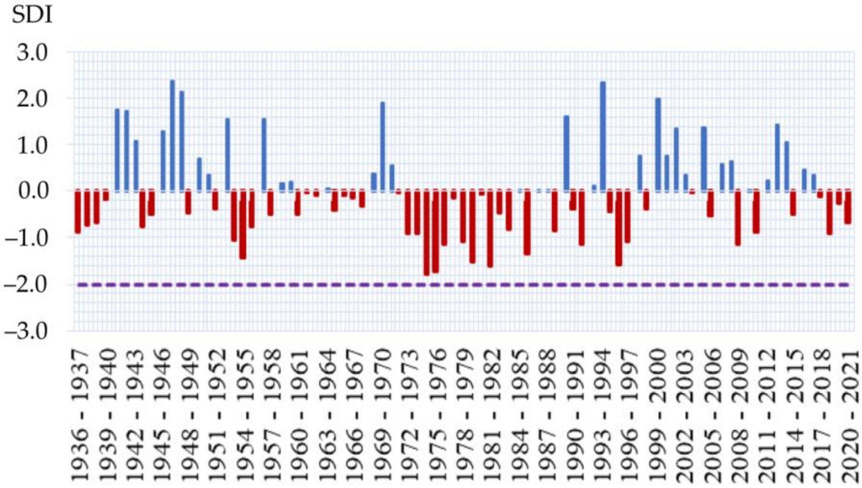


(**c**) Oiyl-Oiyl

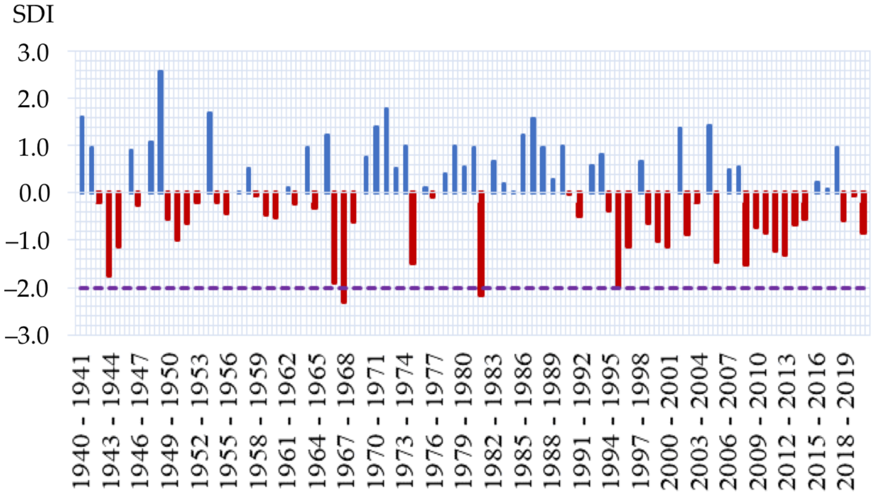
Figure 3. Example of implementation of graphs for SDI for rivers of the Zhaiyk–Caspian water management basin (blue color indicates positive index values, red color indicates negative index values, dotted line-SDI $\leq$ 2.00, indicator of severe drought).

Due to the rather sharp fluctuations in the monthly water discharge dataset, which is typical for the lowland rivers of Kazakhstan [49] and the regulation of many rivers in the study area SDI in the monthly section was not possible. In this work, an annual time step was used to represent SDI, providing a clearer and more easily interpretable characterization of droughts based on hydrological year.

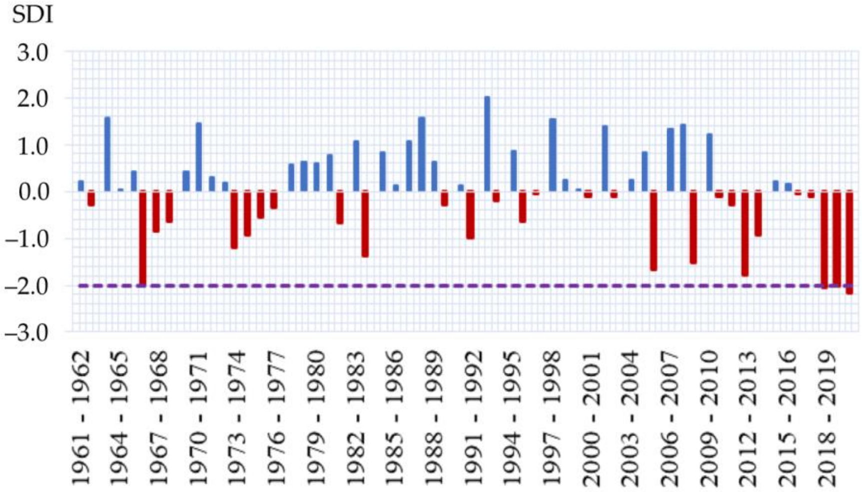
Based on the data generated by the SPI Application, maps were constructed in the ArcGIS 10.8 environment; these are shown in Figure 7. The data were processed using the Spatial Analyst function using the IDW interpolation method.



(**a**) Togyzak-Togyzak

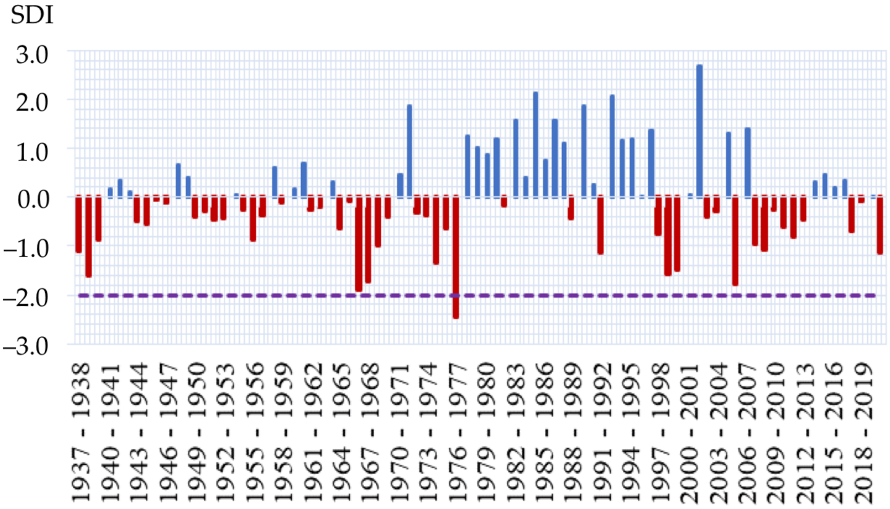


(**b**) Torgay-Tusum Sands

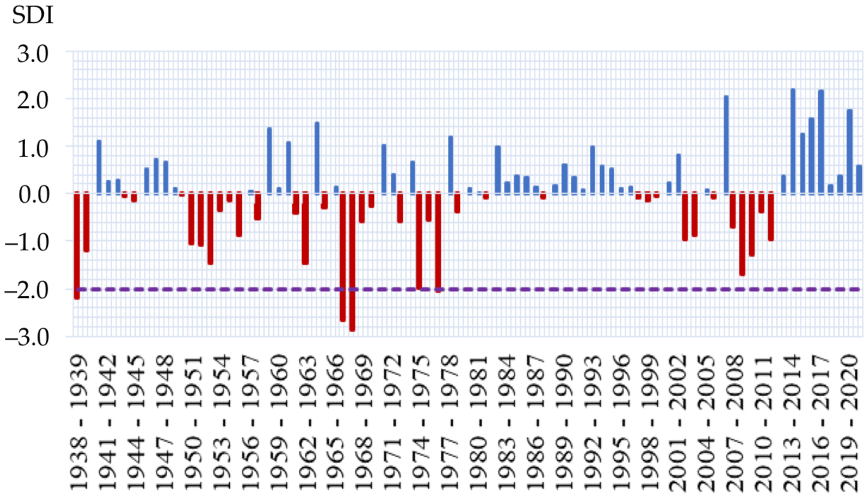


(**c**) Yrgyz—Shenbertal

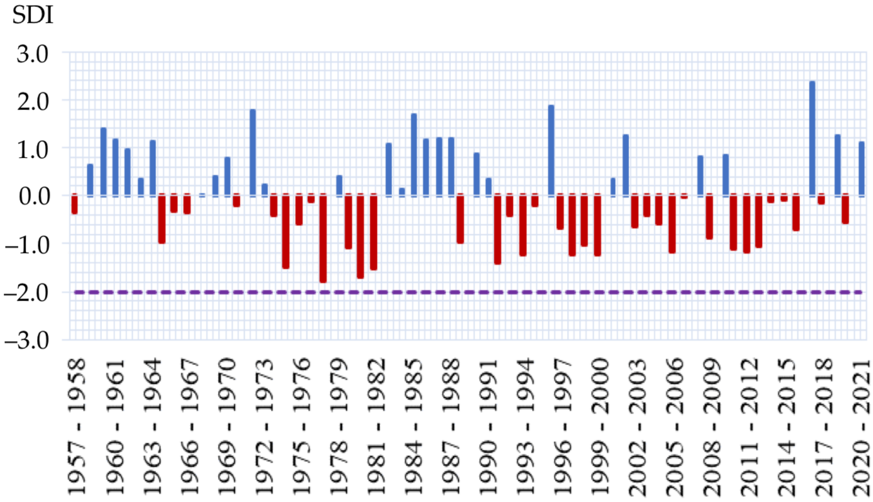
Figure 4. Example of implementation of graphs for SDI for the rivers of the Tobyl–Torgai water management basin (blue color indicates positive values of the index, red color indicates negative values of the index, dotted line-SDI $\leq$ 2.00, indicator of severe drought).



(**a**) Kalkutan-Kalkutan

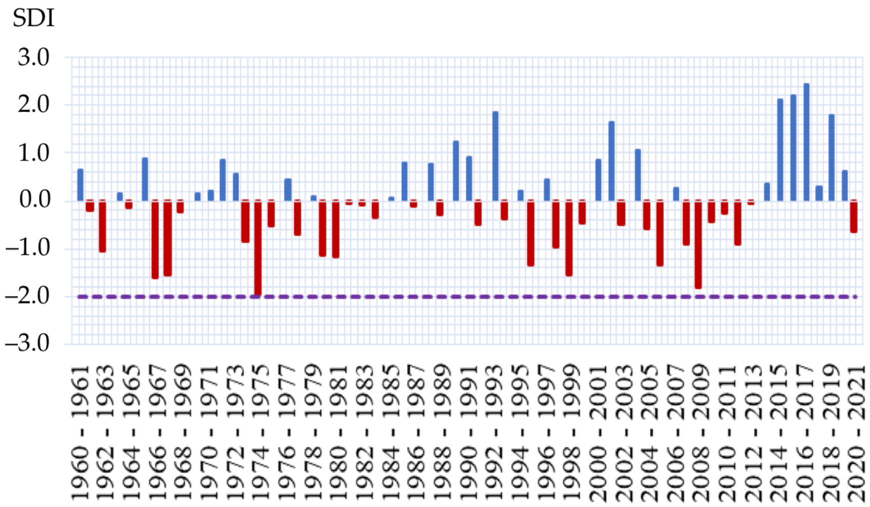


(**b**) Akkanburlyk-Vozvyshenka

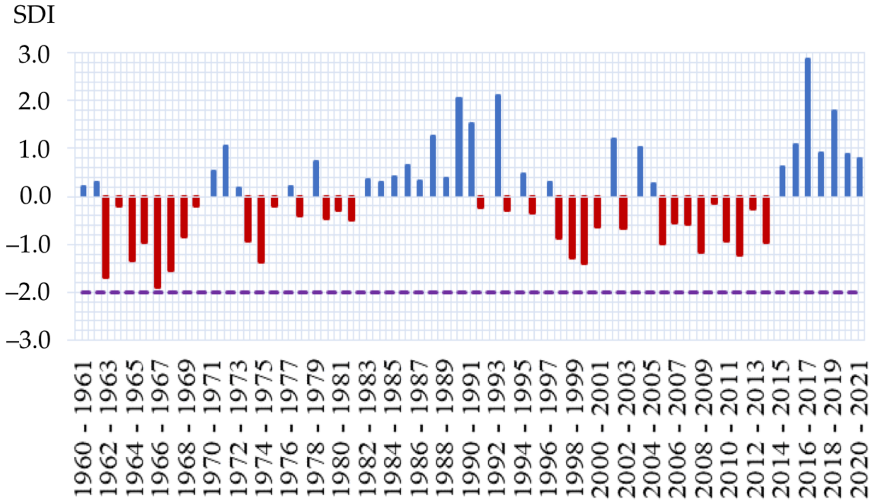


(**c**) Silety—Izobilnoye

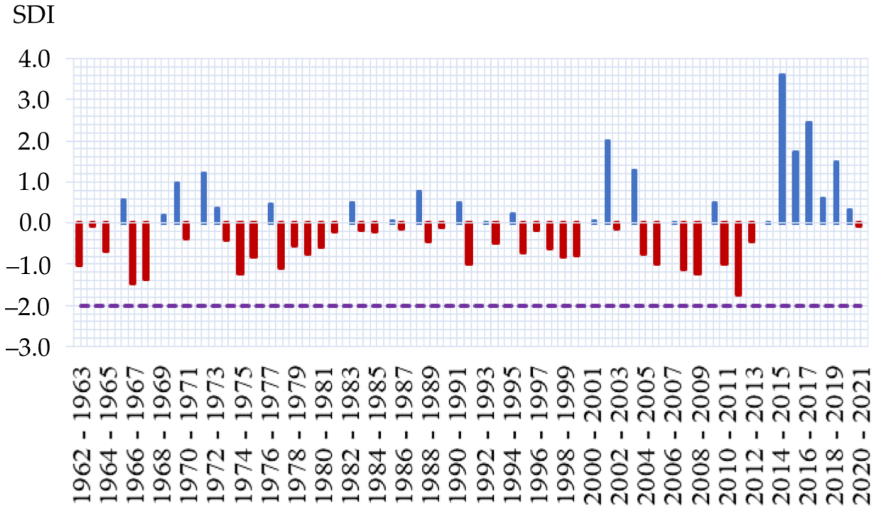
Figure 5. Example of implementation of graphs for SDI for rivers of the Yesil water management basin (blue color indicates positive index values, red color indicates negative index values, dotted line—SDI ≤ 2.00, indicator of severe drought).



(**a**) Sherubainura-Karamuryn



(**b**) Nura-Koshkarbayeva



(**c**) Sarysu-189th Passage

Figure 6. Example of implementation of graphs for SDI for the rivers of the Nura–Sarysu water management basin (blue color indicates positive values of the index, red color indicates negative values of the index, dotted line—SDI $\leq$ 2.00, indicator of severe drought).

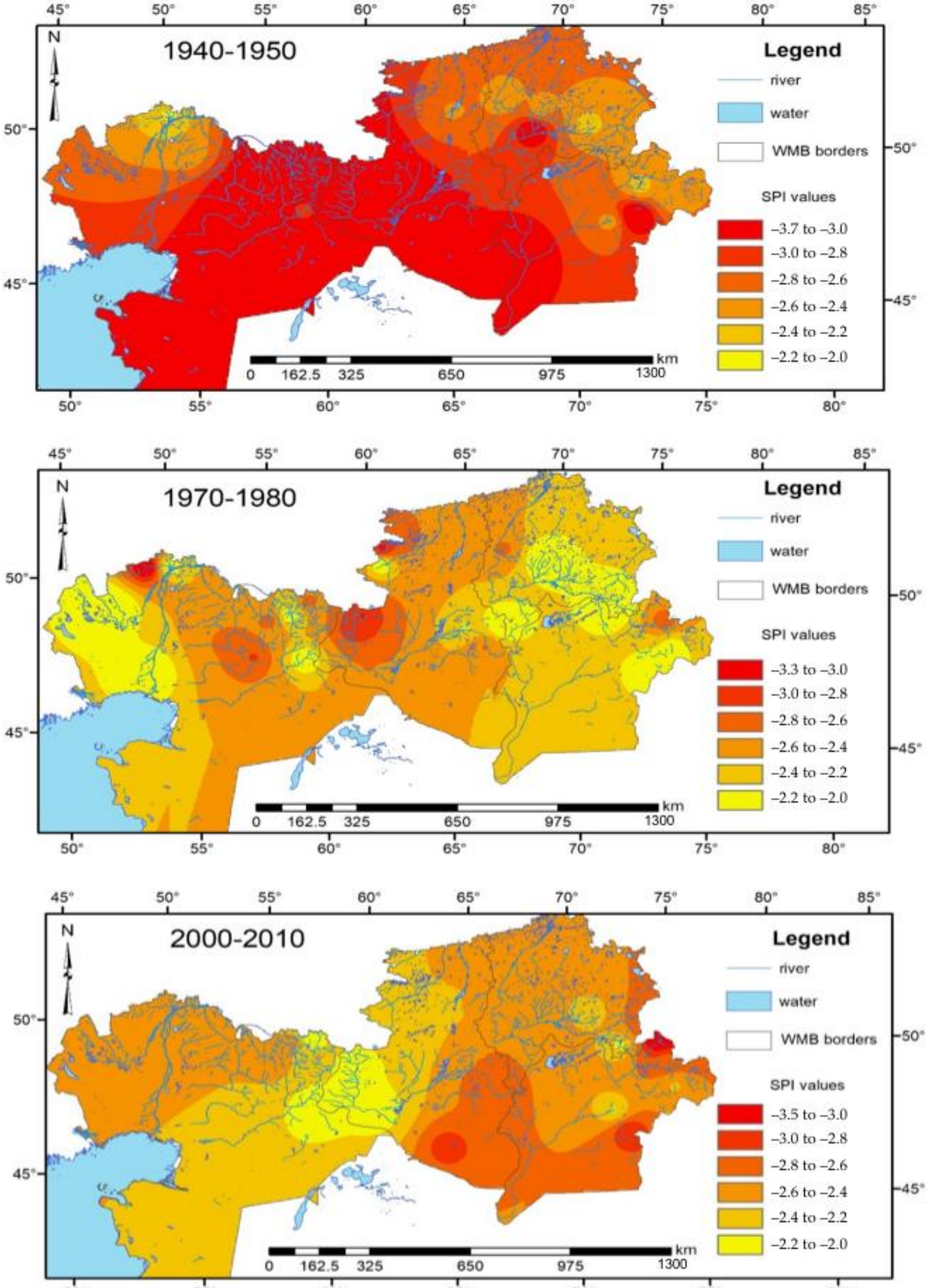


Figure 7. Spatial distribution of hydrological drought by standardized precipitation index (SPI ≤ 2) on the territory of Kazakhstan Plain.

4. Discussion

The results of the spatial distribution of hydrological drought showed that, in the study area, the manifestation of extreme droughts is observed in all time intervals, under a natural flow regime (1940–1950), under a disturbed regime (2000–2010), and even in the intermediate period, covering 1970–1980. It is worth noting that when compared to the

1940s, the SPI values are weakening in the modern period. This fact is explained by less favorable climatic conditions, such as changes in precipitation and temperature regimes, as well as the impact of human activity on natural ecosystems. At the same time, the frequency of hydrological droughts on the territory of lowland Kazakhstan has increased. These results highlight the need for in-depth analysis and monitoring of climatic changes in the region using modern methods and modeling technology to enable the more accurate forecasting and management of risks associated with hydrological anomalies. Table 6 shows the number of cases of hydrological drought for the whole period of instrumental observations, divided into two periods, the first period—conditionally natural—and the second period—modern—caused by the influence of economic activity.

Table 6. Number of hydrological drought events.

Hydrological Post	**Observation Period**	**Whole Observation Period**				**Conditionally Natural Period up to 1973**				**Current Period after 1974**			
		Number of Cases	**SDI$_{min}$**	**Number of Cases**	**SDI$_{max}$**	**Number of Cases**	**SDI$_{min}$**	**Number of Cases**	**SDI$_{max}$**	**Number of Cases**	**SDI$_{min}$**	**Number of Cases**	**SDI$_{max}$**
Zhaiyk–Caspian water management basin													
Zhaiyk-Kushum	1912–2021	64	−1.61	45	3.10	35	−1.61	27	3.10	29	−1.41	18	1.43
Zhaiyk-Makhambet	1932–2021	46	−1.66	43	2.66	22	−1.63	20	2.66	24	−1.66	23	1.75
Shagan-Kamenny	1932–2010	40	−2.17	38	2.14	24	−1.95	18	2.14	16	−2.17	20	1.39
Elek-Shelek	1949–2021	40	−2.48	32	3.06	14	−2.48	11	3.06	26	−2.10	21	1.93
Kosistek-Kosistek	1957–2021	32	−1.94	32	3.82	6	−1.61	11	2.30	26	−1.94	21	3.82
Or-Bogetsay	1932–2021	44	−2.11	44	2.65	20	−2.11	21	2.65	24	−2.10	23	1.33
Shyngyrlau-Kentubek	1954–2021	35	−2.00	32	2.49	7	−1.21	13	2.49	28	−2.00	19	1.45
Kopirankaty-Algabas	1957–2021	28	−2.53	36	1.91	8	−1.99	9	1.05	20	−2.53	27	1.91
Oiyl-Oiyl	1935–2021	47	−2.36	39	3.66	17	−1.49	22	3.66	30	−2.36	17	1.78
Sagyz-Sagyz	1950–1998	22	−2.32	26	1.99	9	−2.32	15	1.99	13	−2.25	11	1.32
Tobyl–Torgai water management basin													
Tobyl-Grishenka	1937–2021	46	−2.07	38	2.48	20	−1.68	38	2.48	26	−2.07	21	2.05
Tobyl-Kostanay	1931–2021	56	−1.50	34	2.67	25	−1.40	34	2.67	31	−1.50	16	2.25
Ayat-Varvaryinka	1952–2021	37	−1.70	32	2.41	12	−1.12	32	2.41	25	−1.70	22	2.37
Togyzak-Togyzak	1936–2021	49	−1.79	36	2.36	22	−1.42	36	2.36	27	−1.79	20	2.34
Obagan-Aksuat	1938–2021	40	−2.75	43	2.32	16	−2.08	43	1.92	24	−2.75	23	2.32
Torgay-Tusum Sands	1940–2021	42	−2.31	39	2.56	18	−2.31	39	2.56	24	−2.15	23	1.57
Karatorgay-Urpek	1941–2021	34	−4.94	46	3.18	14	−2.01	46	3.18	20	−4.94	27	1.41
Sarytorgay-Sarytorgay	1960–2021	28	−3.09	33	2.46	6	−2.05	33	2.46	22	−3.09	25	1.31
Uly Zhylanshyk-Korgantas	1958–1987	16	−2.08	13	2.05	10	−2.08	13	1.53	6	−1.27	7	2.05
Damdy-Damdy	1955–2021	34	−3.84	32	2.38	9	−2.72	32	1.93	25	−3.84	22	2.38
Yesil water management basin													
Kalkutan-Kalkutan	1937–2021	46	−2.45	38	2.68	25	−1.89	12	1.88	21	−2.45	26	2.68
Zhabay-Atbasar	1937–2021	49	−1.86	36	3.94	24	−1.86	14	1.89	25	−1.49	22	3.94
Akkanburlyk-Vozvyshenka	1938–2021	37	−2.87	46	2.19	20	−2.87	16	1.49	17	−2.05	30	2.19
Imanburlyk-Sokolovka	1950–2021	34	−2.01	37	2.55	15	−2.01	9	0.60	19	−1.72	28	2.55
Silety-Izobilnoye	1957–2021	36	−1.77	28	2.36	6	−0.95	11	1.77	30	−1.77	17	2.36
Nura–Sarysu water management basin													
Nura-Besoba	1960–2021	31	−2.05	30	2.95	7	−1.58	7	0.85	24	−2.05	23	2.95
Nura-Sheshenkara	1960–2021	35	−1.84	26	3.03	8	−1.67	6	0.89	27	−1.84	20	3.03
Nura-Balykty	1960–2021	28	−2.57	33	2.99	11	−2.57	3	0.42	17	−1.63	30	2.99
Nura-Koshkarbayeva	1960–2021	32	−1.87	29	2.86	9	−1.87	5	1.05	23	−1.40	24	2.86
Sherubainura-Karamuryn	1960–2021	33	−1.96	28	2.44	7	−1.58	7	0.87	26	−1.96	21	2.44
Sarysu-189th passage	1962–2021	35	−1.73	24	3.61	7	−1.45	5	1.22	28	−1.73	19	3.61
Zhamansarysu-Atasu	1960–2021	44	−1.08	17	3.43	9	−0.74	5	1.46	35	−1.08	12	3.43

4.1. *Zhaiyk–Caspian Water Management Basin*

Analysis of Table 5 reveals that 80% of hydrological stations within this water management basin experienced an increase in drought occurrences during the modern period.

Here is a breakdown by river: the Zhaiyk River saw an increase from 22 cases in the conditionally natural period to 24 cases in the modern period. Similarly, the Elek River witnessed a rise from 14 cases to 26 cases. Likewise, the Kosistek, Shyngyrlau, and Oiyl Rivers exhibited increases, with cases rising from 6 to 26, 7 to 28, and 17 to 30, respectively.

4.2. Tobyl–Torgai Water Management Basin

Ninety percent of hydrological stations in this water management basin show an increase in drought occurrences during the modern period. For instance, the Ayat River exhibited a two-fold increase, rising from 12 cases in the conditionally natural period to 25 cases in the modern period. Similarly, the Sarytorgai River witnessed a significant rise, with cases quadrupling from 6 to 22. The Damdy River also experienced a substantial increase, with cases tripling from 9 to 25. However, the Uly-Zhylanshyk River stands as an exception, exhibiting a two-fold decrease in drought events.

4.3. Yesil Water Management Basin

This basin reveals a particularly significant rise in drought occurrences on the Silety River during the modern period. Here, the number of cases has increased fivefold, jumping from 6 in the conditionally natural period to 30 in the modern period. Notably, changes on other rivers within this water management basin appear less substantial.

4.4. Nura–Sarysu Water Management Basin

Analysis of Table 5 reveals a universal increase in drought occurrences across all hydrological stations (100%) within this basin during the modern period. The magnitude of this increase varies across rivers. The Nura River exhibited a three-fold rise, with cases jumping from 8 in the conditionally natural period to 27 in the modern period. Similarly, the Sherubainura, Sarysu, and Zhamansarysu Rivers all experienced substantial increases, with cases quadrupling on each river (from 7 to 26, 7 to 28, and 9 to 35, respectively).

This study investigated the influence of negative standardized drought index (SDI) values on the defining groups of hydrological drought events within two periods: the conditionally natural period and the modern period. The goal was to calculate the frequency (recurrence of dry periods exceeding two years) and average duration of these events (Figures 8–11). All four water basins of the Republic of Kazakhstan exhibited changes in drought frequency and duration between the two periods.

The Zhaiyk–Caspian basin saw a significant increase in the frequency of dry year groupings compared to the past. Notably, occurrences of three consecutive drought events doubled from 14 to 24, while four consecutive events tripled from 5 to 14. The modern period also witnessed a rise in prolonged droughts, with eight consecutive dry years occurring three times compared to only one instance in the conditionally natural period. Furthermore, groupings of eleven and thirteen consecutive dry years were observed solely within the modern period.

Similar trends were observed in the Tobyl–Torgai basin, with an increase in the frequency of most dry year groupings during the modern period. However, the three-year occurrences showed a slight decline. The occurrence of four consecutive dry years doubled in frequency, and the modern period also witnessed prolonged droughts not observed previously, with two instances of ten consecutive dry years.

The Yesil basin displayed a different pattern. Here, three consecutive dry year groupings increased from five to eleven cases, while four consecutive occurrences saw a slight increase from five to six cases. Notably, the modern period observed previously unseen six-year low-water periods (four cases) but lacked the seven-year groupings observed in the conditionally natural period.

Finally, the Nura–Sarysu basin exhibited a substantial increase in the frequency of four consecutive dry years, rising from one case to three in the modern period. Additionally, prolonged droughts of five, eight, nine, and eleven years emerged during this period, which were not observed earlier.

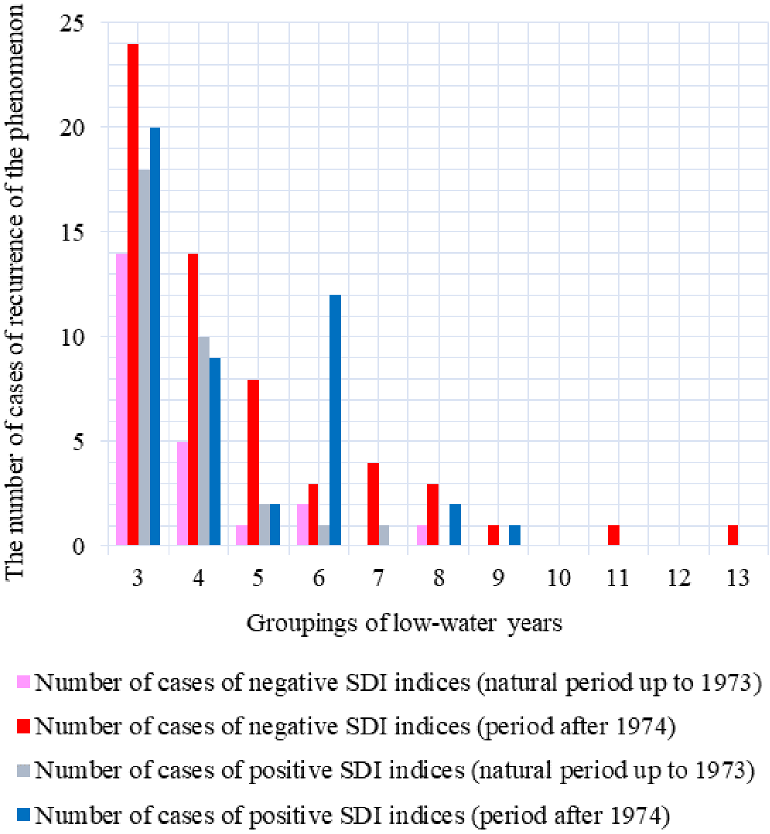


Figure 8. Groupings of low-water years in the Zhaiyk–Caspian water management basin.

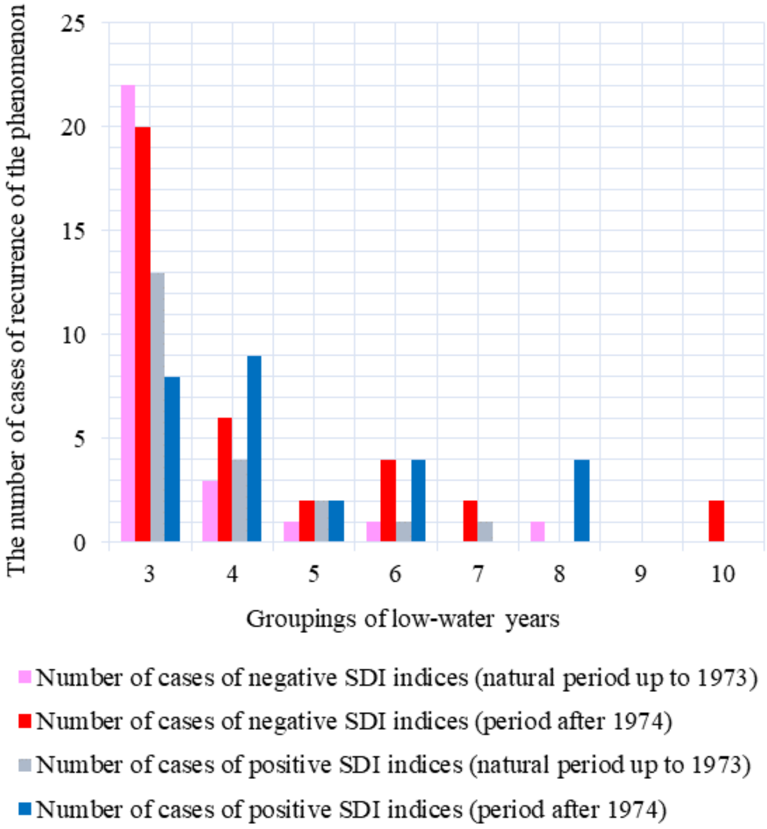


Figure 9. Groupings of low-water years in the Tobyl–Torgai water management basin.

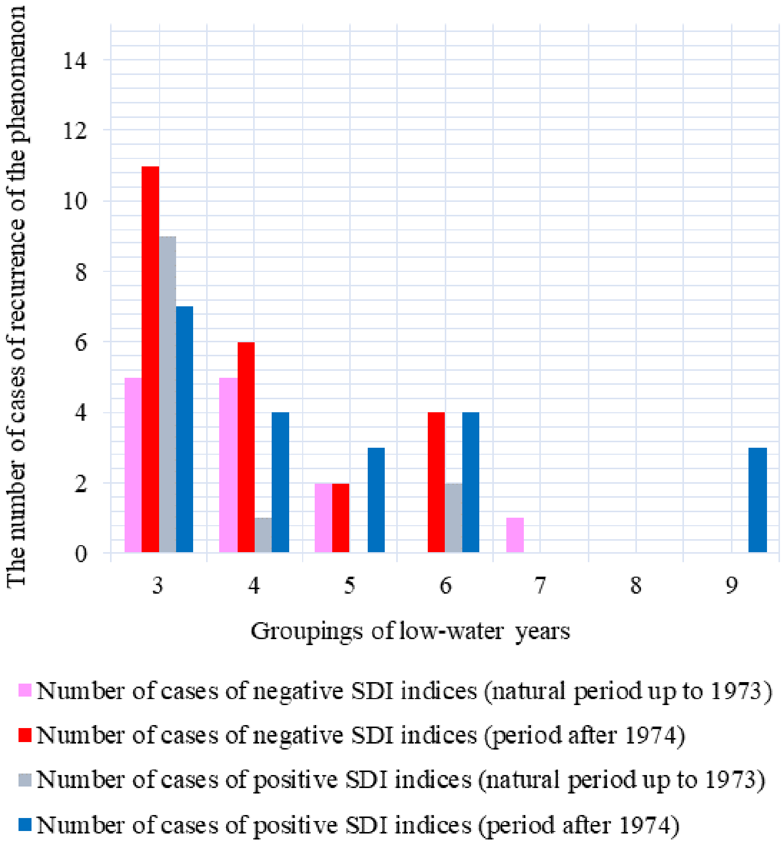


Figure 10. Groupings of low-water years in the Yesil water management basin.

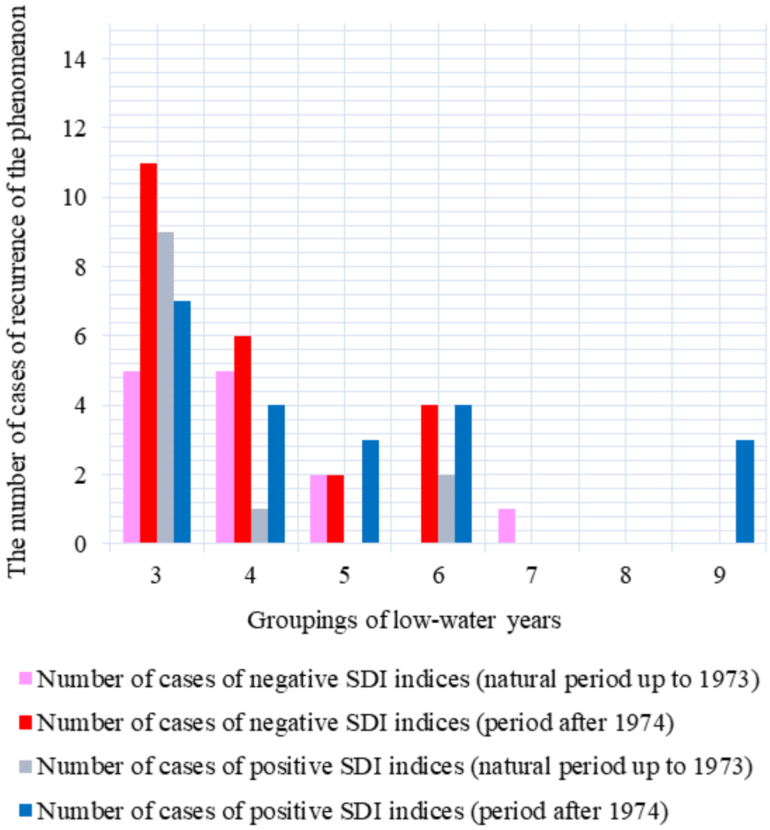


Figure 11. Groupings of dry years in the Nura–Sarysu water management basin.

5. Conclusions

The analysis of spatial and temporal changes in hydrometeorological characteristics reveals several key observations. Notably, the most severe hydrological droughts occurred in the first half of the 20th century, particularly during the 1930s. This finding is corroborated by the long-term river flow data. Furthermore, the analysis indicates that hydrological droughts persist under present-day conditions. However, there is a concerning trend towards shorter intervals between drought events, suggesting potential climatic changes and alterations in the hydrological regimes of the studied water management basins. Additionally, the SPI reaches extremely low values in some instances, highlighting the high intensity of recent droughts.

The analysis of hydrological drought occurrences (SDI) in Kazakhstan's water management basins across the conditionally natural and modern periods reveals a concerning trend. All basins exhibit a significant increase in drought events during the modern period. Notably, the Zhaiyk–Caspian basin demonstrates a rise in drought cases at most monitoring stations, suggesting a general shift towards more frequent droughts. Similarly, the Tobyl–Torgai basin witnesses a substantial increase in drought occurrences across most stations, with the exception of the Uly-Zhylanshyk River. The Yesil basin showcases a distinct pattern, with a significant increase observed only on the Silety River, potentially indicating localized changes in hydrological conditions. Finally, the Nura–Sarysu basin displays the most dramatic rise, with all hydrological stations recording a significant increase in drought events.

The analysis of dry year groupings across Kazakhstan's water management basins during the conditionally natural and modern periods reveals a concerning trend in terms of the increased frequency and duration of low-water periods. All basins exhibit a rise in the number of dry year groupings in the modern period compared to the past. The Zhaiyk–Caspian basin showcases a significant increase in both three- and four-year low-water spells, alongside the emergence of previously unobserved extended dry periods. The Tobyl–Torgai basin, while experiencing a general increase in dry year groupings, displays a slight decrease in three-year occurrences. The Yesil basin exhibits a rise in three- and four-year low-water periods, with the appearance of six-year groupings and the disappearance of seven-year ones. Finally, the Nura–Sarysu basin demonstrates a substantial increase in four-year dry spells, coupled with the emergence of new extended low-water periods not observed earlier. These findings highlight a potential intensification of drought severity and duration in Kazakhstan's water management basins.

These observations point towards a concerning trend: an increase in both the duration and frequency of low-water periods across Kazakhstan's water management basins under current conditions. This finding suggests potential alterations in the region's climatic and hydrological regimes, potentially driven by climate change.

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