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Reaction of Minimal Streamflow to Natural Factors in the Context of Climate Uncertainty

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Abstract
This study analyzes long-term changes in minimal streamflow in the Zhaiyk-Caspian Water Management Basin (WMB), Western Kazakhstan, under climate variability. Using extensive hydrometeorological datasets (monthly discharge and daily meteorological records) from 1940 to 2021, the research assesses trends in low-flow characteristics across 18 hydrological posts. The analysis distinguishes two climatic periods: climate stabilization (pre-1973) and climate change (1974–2021). The methodology integrates hydrological and statistical analyses, including minimal monthly discharges, low-flow durations, soil freezing depths, and thaw frequencies. Findings reveal a widespread increase in winter low flows—up to 5.2 times—due to reduced frost depths and more frequent thaw events, enhancing groundwater contributions. Conversely, summer-autumn flows declined in several rivers, with drying trends linked to rising air temperatures and precipitation deficits. This study offers a novel, regionally adapted methodology for characterizing minimal streamflow under climate change, providing critical insights for hydrological drought assessment and water resource planning in arid and semi-arid environments.

Keywords Minimal streamflow · Economic activity · Hydrological drought · Low-flow period · Soil freezing depth · Thaw

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1 Introduction

Recent hydrometeorological studies have documented substantial alterations in river flow regimes resulting from climate change, underscoring the critical need to assess variations in river discharge—particularly minimum streamflows, which are vital for sustainable water management (Alimkulov et al. 2024a, b; Birimbayeva et al. 2024). With rising water demands across industrial, agricultural, and municipal sectors, managing low-flow periods has become increasingly complex (Alimkulov et al. 2024a). Foundational work by Vladimirov (1966, 1967, 1970) and Norvatov (1956) established the importance of minimal flow in maintaining ecological balance and public health, especially during periods of hydrological stress. More recent studies have examined the impacts of climatic variability on low-flow regimes in different regions (Liebscher 1983; Arnell 1989; Wilby et al. 1994; Tigkas et al. 2012), while also recognizing the challenges posed by limited data availability and the lack of universally accepted definitions of "low water" (Koronkevich et al. 2010).

Hydrological droughts—marked by low river discharge and reduced groundwater levels—have broad environmental, economic, and social consequences (Smakhtin 2001; Al-Faraj and Tigkas 2016; Karlin et al. 2008). Although low-flow periods may coincide with drought conditions, their causes and dynamics are often distinct (Tallaksen et al. 1997; Alekseevskij and Frolova 2011). Accurate assessment of minimal streamflow requires distinguishing between summer-autumn and winter low-flow phases and understanding the role of baseflow contributions (Opperman 2006a, b; Querner et al. 1983; Reilly and Kroll 2003; Richter et al. 1996, 1997, 1998; Telis 1990)

As climate change accelerates, conventional hydrological models based on stationarity assumptions have become less reliable. There is a growing need for adaptive approaches to estimate minimal runoff under changing climatic and anthropogenic pressures (Sivokhip et al. 2021). In this context, Thomas et al. (2011) reviewed strategies to maintain minimal flow in small rivers, emphasizing the importance of regional adaptation. This is particularly relevant in Western Kazakhstan, where high industrial water demand—especially from oil and gas operations—intensifies water scarcity risks.

Despite progress in low-flow research, most existing studies focus on large river systems, leaving small and medium-sized rivers in arid and semi-arid zones comparatively understudied. Addressing this gap, the present study investigates long-term changes in minimum streamflow across the Zhaiyk-Caspian Water Management Basin. The novelty of the work lies in its adaptation of traditional hydrological methods to current climate conditions and its identification of key natural factors influencing summer-autumn and winter low-flow regimes. These insights provide a foundation for scenario-based forecasting and adaptive water management in vulnerable river basins.

2 Materials and Methods

2.1 Description of the Study Area

The Zhaiyk-Caspian Water Management Basin (WMB), located in Western Kazakhstan, spans 736,241 km² across the Aktobe, West Kazakhstan, Atyrau, and Mangystau regions. Bordered by Russia, Uzbekistan, Turkmenistan, and several Kazakh regions, it is the coun-

try's largest and economically significant basin, supporting over 3 million people (15.6% of the national population). The regional economy is driven by oil and gas, agriculture, and fisheries. The basin includes over 1,500 rivers and ephemeral watercourses exceeding 45,000 km in length, with major rivers such as the Zhaiyk (Ural), Oyil, Zhem, and Sagyz, and distributaries like the Volga-Kigach and Sharanovka (Gal'perin et al. 2012; Iskakov and Medeu 2006; Sarsekov et al. 2017; Petrishchev et al. 2017; Turgumbaev and Turikeshev 2018; Akiyanova et al. 2012; Koshim 2010). Figure 1 illustrates the study area, including hydrological posts and meteorological stations.

Industrial development is a key driver of economic growth in the study area, with rapid expansion of oil and gas production since the early 2000 s leading to a substantial rise in water demand. Between 2000 and 2021, industrial water use in Kazakhstan increased by 44%, from 66.56 to 118.51 million m^3/year, highlighting growing water scarcity risks. This trend, alongside existing freshwater deficits, emphasizes the need for sustainable water management. Recommended strategies include reducing freshwater withdrawals, minimizing wastewater discharges, promoting water reuse, and implementing closed-loop systems. Improving industrial water efficiency through low-waste and waste-free technologies is critical for balancing productivity with environmental sustainability in arid regions.

2.2 Available Data

In this study, official cadastral records of average monthly river discharge and meteorological data on average daily air temperature and daily precipitation totals, provided by RSE "Kazhydromet", were used to assess changes in minimal runoff. The Zhaiyk-Caspian Water Management Basin (WMB) was subdivided into several hydrologically homogeneous areas based on zonal and azonal factors, orographic conditions, and the spatial distribution of river networks.

Hydrological posts were selected to represent diverse physiographic settings that influence flow generation, with preference given to river sections exhibiting minimal direct anthropogenic influence. For stations affected by human activities—such as reservoir regulation or diversion—the observed discharge data were corrected to reflect natural flow conditions.

The following hydrological parameters were used in the analysis: minimal monthly water discharge during the summer-autumn low-flow period and during the winter low-flow period; the start and end dates of both low-flow periods; and the duration of each period. To evaluate the influence of climatic factors on the summer-autumn low-flow period, mean daily air temperatures (averaged over the period) and cumulative daily precipitation totals were analyzed. For the winter low-flow period, contributing factors were assessed using the sum of negative mean daily air temperatures (expressed as absolute values) and the measured depth of soil freezing.

All calculations were conducted for two distinct time intervals: the climate stabilization period (from the beginning of instrumental observations until 1973) and the climate change period (1974–2021), reflecting shifts in climatic conditions and their potential hydrological impacts.

The list of hydrological posts used for calculations and their corresponding hydrologically homogeneous areas is provided in Table 1.

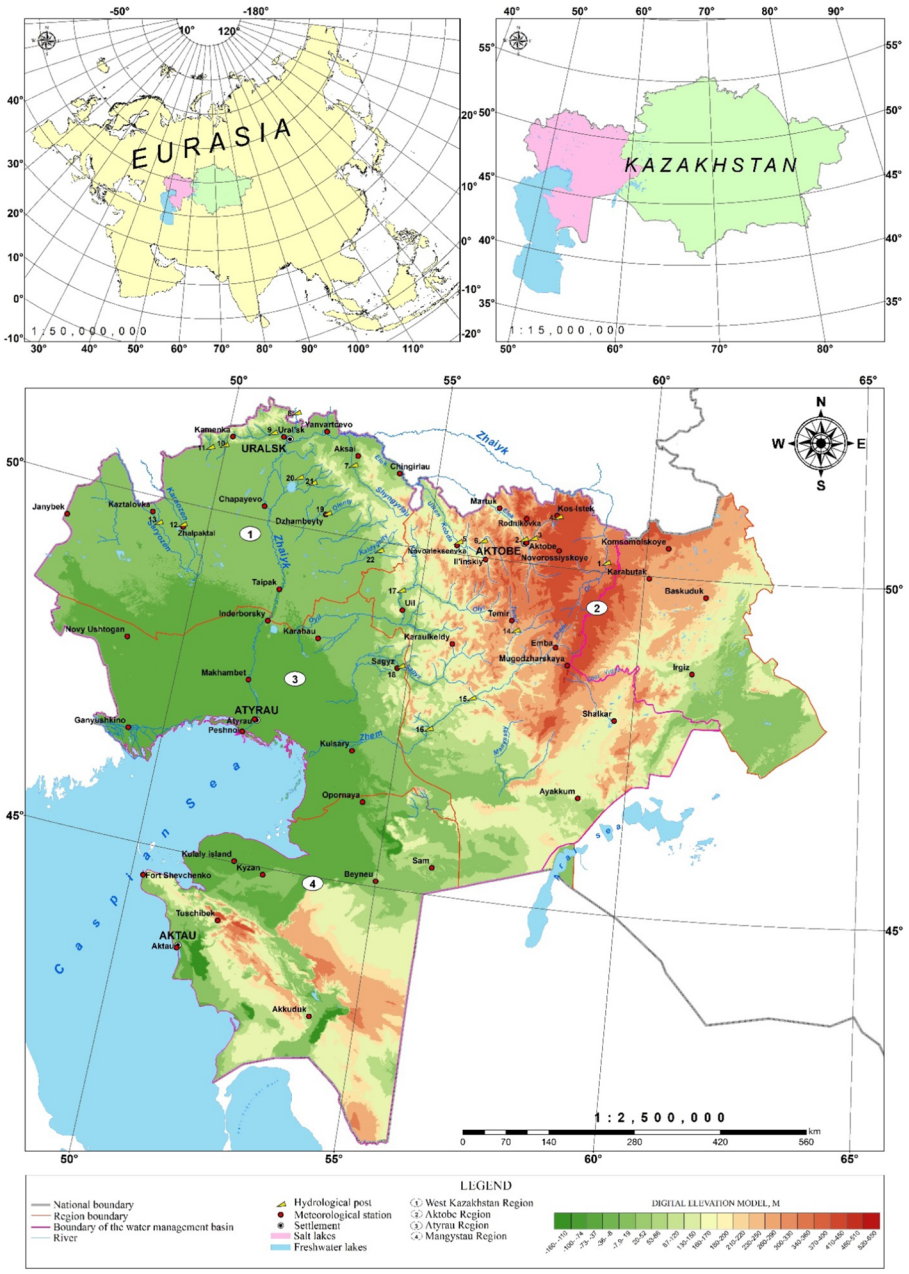


Fig. 1 Overview map of the study area and location of hydrological posts and meteorological stations of the Zhaiyk-Caspian water management basin

Table 1 Hydrological posts of the Zhaiyk-Caspian water management basin

N°	Hydrological area	River–hydrological post	Distance from the mouth, km	Watershed area, km^2	Weighted average catchment height, m	Period of climate stabilization	Period of changes in climatic characteristics
1	Left-bank tributaries of the Zhaiyk River	Or–Bogetsay	208	7480	350	1957–1973	1974–2021
2		Elek–Aktobe	501	11,000	340	1940–1973	1974–2021
3		Kargaly–Kargalinskoye	7	5000	370	1940–1973	1974–2021
4		Kosistek–Kosistek	24	281	430	1957–1973	1974–2021
5		Ulken Kobda–Kobda	172	8110	240	1940–1973	1974–2021
6		Karakobda–Alpaisai	24	2240	270	1963–1973	1974–2021
7		Shyngyrlau–Kentubek	87	4660	130	1954–1973	1974–2021
8	Right-bank tributaries of the Zhaiyk River, rivers of the Western part of the Obschiy Syrt	Shagan–Kamenny	116	4000	130	1940–1973	1974–2021
9		Derkul–Beles	54	1820	101	1963–1973	1974–2021
10		Shyzhyn 1–Chizha 1	50	456	100	1953–1973	1974–2021
11		Shyzhyn 2–Chizha 2	49	509	100	1953–1973	1974–2021
12	Southern rivers of the basin	Temir–Leninsky	96	5310	280	1945–1973	1974–2021
13		Zhem–Zharkamys	403	26,000	260	1940–1973	1974–2021
14		Oyil–Altykarasu	706	6997	230	1940–1973	1974–2021
15		Oyil–Taltogay	459	17,000	200	1940–1973	1974–2021
16	Rivers of the eastern part of the Caspian Lowland	Kuperankaty–Algabas	5	723	80	1964–1973	1974–2021
17		Sholakankaty–Ankatinsky	26	537	70	1964–1973	1974–2021
18		Olenty–Zhympity	127	1290	80	1964–1973	1974–2021
19		Kaldygaity–Zhigerlen	179	2510	140	1964–1973	1974–2021

2.3 Research Methods

The study employed a combination of hydrological and statistical methods for processing and analyzing the hydrometeorological dataset. Standard hydrological calculations were performed in accordance with the Code of Rules for Hydrological Characteristics (2004). Statistical analysis of long-term series was conducted using Fisher's F-test, Student's t-test, and the Mann-Kendall Z_0-test to detect trends and assess the significance of observed changes.

To evaluate the influence of economic activities on flow regimes, a combination of water balance, integral, and statistical methods was applied. The duration of the frost period was determined using the method proposed by Khayrullin (1969), which defines the onset of the frost period as the first occurrence of five consecutive days with maximum daily air temperatures below 0 °C. The period ends when the mean daily temperature consistently rises above 0 °C. The total number of days between these thresholds was taken as the frost period duration. Additionally, the following indicators were used:

- Number of Days with Thaw (N_{d0}): A day with thaw is defined as a day where Tmax ≥ 0 °C within the frost period.
- Number of Thaw Periods (N_0): A thaw period is considered uninterrupted if the maximum temperature does not fall below 0 °C for more than one day. The duration of thaw periods can vary from one day to a month or longer.
- Number of Days with Air Temperature Exceeding 0 °C (Nd↕0): A day with an air temperature exceeding 0 °C is defined as a day when Tmax > 0 °C and Tmin < 0 °C.

The indicator of frost period stability (K) is calculated via Eq. 1:

$$K = \frac{D_{SFP-N_{d0}}}{D_{SFP}} \times 100\% \tag{1}$$

Where D_{SFP} is the duration of the stable frost period, and N_{d0} is the number of days with thaw. If there are no thaw periods (i.e., the frost period is absolutely stable), then K=100%. If the number of days with thaw is half the duration of the frost period, then K=50%.

The calculation of soil freezing depth was based on the absolute values of the cumulative negative air temperatures during the cold period, combined with information on the mechanical composition of soils in the region. This approach allows for spatially differentiated estimation of frost depth, which is essential for assessing its influence on winter runoff dynamics.

The overall methodology adopted in this study is structured according to the workflow presented in Fig. 2. It integrates long-term hydrological and meteorological datasets, including minimal monthly river discharge, daily air temperature, and daily precipitation records. These datasets form the basis for the evaluation of low-flow conditions and their driving climatic and environmental factors.

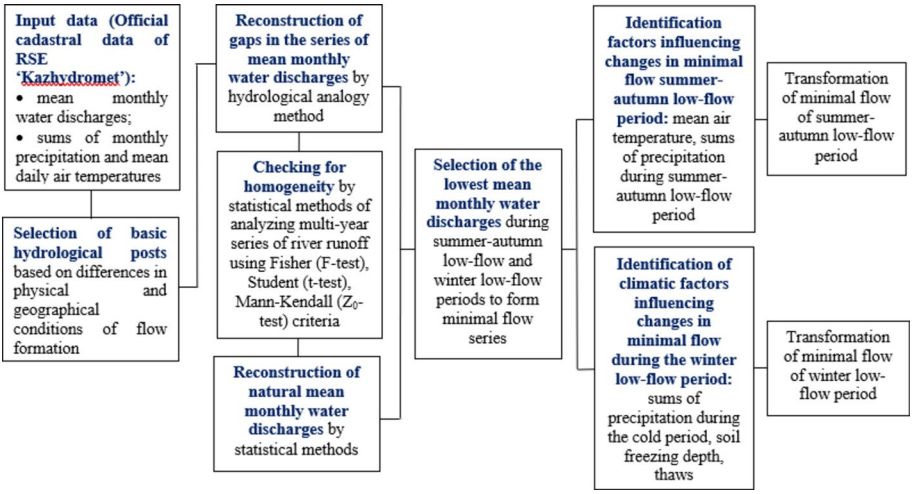


Fig. 2 Workflow of the methodology

3 Results

3.1 Results for the Summer-Autumn Low-Flow Period

Runoff trends during the summer-autumn season in the Zhaiyk-Caspian WMB exhibit significant spatial and temporal variability. The duration of minimal flow is closely tied to the stability of the low-flow period, which is mainly controlled by precipitation availability and flood occurrence. In many rivers, desiccation occurs at the peak of runoff depletion due to groundwater exhaustion. Multi-year trends in minimal mean monthly flow generally follow precipitation patterns and are inversely correlated with air temperature (Fig. 3). For instance, the Ulken Kobda and Kara Kobda rivers showed flow reductions of 23% and 28%, respectively, linked to an 8% decrease in precipitation and a 6-day shortening of the low-flow period. In contrast, rivers such as the Elek, Kargaly, Or, and Kosistek recorded increases in minimal flow—up to 1.5 times—associated with a 13% rise in precipitation at MS Aktobe and extensions of the low-flow period by up to 20 days. Across the basin, average air temperatures during the summer-autumn low-flow period rose by approximately 1 °C, with the highest increase (1.1 °C) observed at MS Novoalekseevka.

The right-bank tributaries of the Zhaiyk River and rivers in the western Obschiy Syrt frequently exhibited zero minimal mean monthly flows during the summer-autumn period. Zero-flow occurrences on the Shyzhyn 1 and Shyzhyn 2 rivers increased from 44% to 57% (pre-1973) to 81% and 94%, respectively, during the climate change period. The Derkul River showed consistent desiccation throughout all recorded years, linked to a 1 °C rise in temperature and a 12% decline in precipitation. In contrast, the Shagan River maintained flow, with a 2.6-fold increase in minimal discharge associated with an 18% rise in precipitation. For both rivers, the low-flow period extended by 6–9 days and began earlier in the post-1973 period.

In the eastern Caspian Lowland, rivers such as Olenty, Kopyrankaty, Buldyrty, Kaldygayty, and Shiderty have experienced complete summer-autumn drying since 1975,

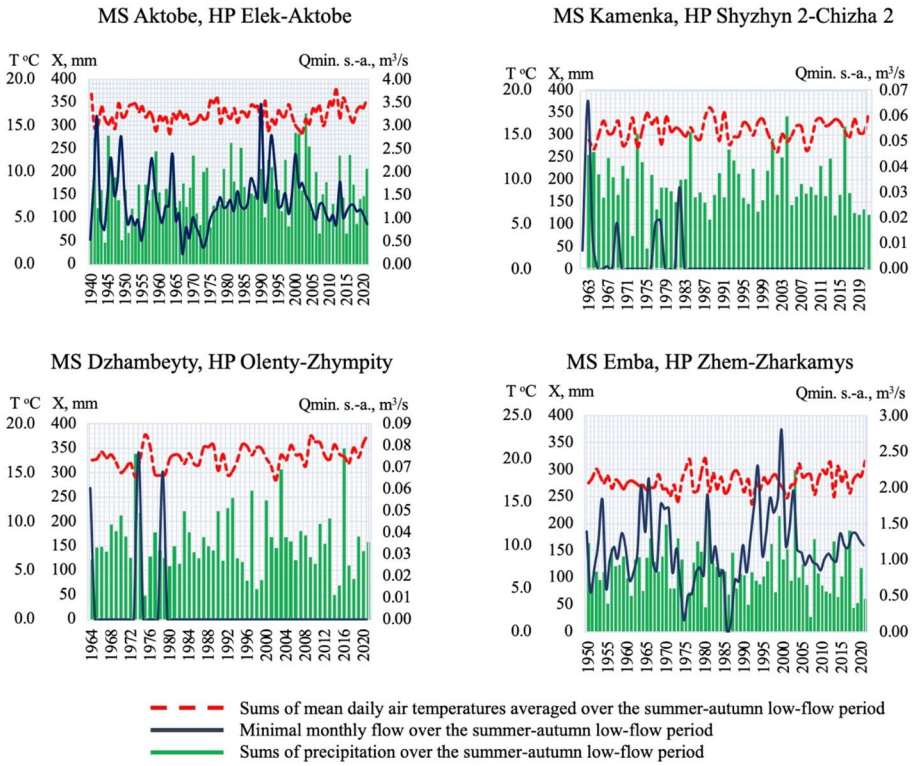


Fig. 3 Dynamics of hydrometeorological characteristics of summer-autumn low-flow period of the Zhaiyk-Caspian water management basin

with dry phases lasting 6–7 months. Zero-flow frequency rose from 59 to 90% to 98–100%, driven by a 1 °C increase in air temperature and a 13% drop in precipitation. The Olenty River showed no major change in low-flow duration, though its start and end shifted 2–3 days earlier.

In the southern basin, trends were mixed: the Zhem and Temir rivers experienced 23% and 37% decreases in flow, while the Oyil River at Taltogai showed a 1.1-fold increase. Across the region, summer-autumn air temperatures rose by ~1.0 °C, and precipitation declined by 1–15%. The low-flow period extended by 5–7 days on these rivers, starting earlier and ending slightly later.

3.2 Results for the Winter Low-Flow Period

Variability in winter meteorological conditions—particularly winter precipitation and the frequency and intensity of negative daily air temperatures—plays a critical role in determining winter runoff, primarily through its influence on soil freezing depth and groundwater drainage capacity. During the period of climatic change, reductions in soil frost depth have been associated with increases in winter discharge. Analysis indicates a clear correlation: lower cumulative negative air temperatures and shallower soil freezing are linked to higher winter streamflow volumes (Fig. 4).

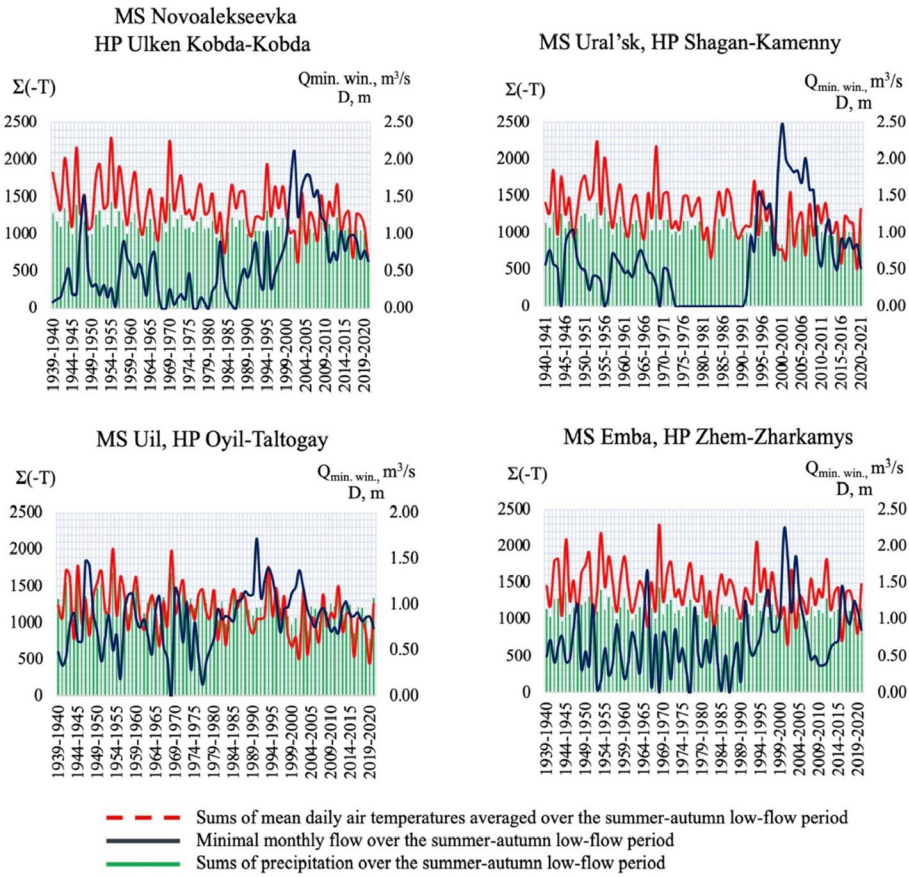


Fig. 4 Dynamics of hydrometeorological characteristics of summer-autumn low-flow period of the Zhaiyk-Caspian water management basin

During the climate change period, winter discharge on the left-bank tributaries of the Zhaiyk River increased significantly—on average by 2.5 times—particularly on the Kosistek, Kargala, and Elek rivers. This rise coincided with a 15% average decrease in the sum of negative daily air temperatures and an 8% reduction in soil freezing depth, with the most pronounced changes observed at MS Aksai. Similar trends were noted on the right-bank tributaries and rivers of the western Obschiy Syrt, such as the Shagan River, which saw a 1.3-fold increase in winter flow. However, zero-flow frequencies increased sharply on rivers like Derkul, Shyzhyn-I, and Shyzhyn-II—reaching up to 98% in the Derkul.

In the eastern Caspian Lowland, complete winter desiccation became widespread post-1973, with zero-flow frequencies rising to 98–100%, linked to a 19% drop in negative temperature sums and a 10% decrease in soil frost depth. Southern rivers (Oyil, Sagyz, Zhem) showed increases in winter flow by up to 2.8 times, while experiencing 14–17% reductions in negative temperature sums and a 9% average reduction in soil freezing depth. Overall, long-term data reveal a notable decrease in soil freezing depths—from an average of 114 cm before 1973 to 104 cm during 1974–2021—highlighting the regional impacts of climate

warming on cold-season hydrology. Figure 5 presents the spatial distribution of average soil freezing depths in the Zhaiyk-Caspian WMB for the 1974–2021 period.

The decline in soil freezing depth across the Zhaiyk-Caspian WMB from 1974 to 2021 is primarily driven by rising winter air temperatures. Over this period, average frost depth decreased by 10 cm (a 9% reduction), reflecting broader hydrological shifts such as reduced spring runoff and prolonged low-flow periods—leading to a more uniform annual hydrograph. These changes are linked to more frequent winter thaws and enhanced baseflow.

The variability in soil freezing is further influenced by a shortening of the stable frost period and a consistent increase in thaw events. Key temperature thresholds (e.g., −5 °C, 0 °C, +5 °C, +10 °C) are useful for tracking interannual climatic transitions, with the upward crossing of 0 °C marking the onset of snowmelt and soil drying. The duration of the stable frost period—defined as the number of consecutive days with sub-zero mean daily temperatures—has declined across the basin during the climate change period, as shown in Fig. 6.

Across the Zhaiyk-Caspian WMB, the duration of the stable frost period has decreased significantly since 1973 due to rising winter air temperatures. In the Aktobe Region, the average frost period declined from 146 to 142 days, with reductions of up to 7 days at MS Ayakkum, Mugodzharskaya, Irgiz, and Aktobe. In West Kazakhstan, the frost period shortened from 138 to 130 days, with the largest decreases (12–15 days) at MS Dzhanybek, Zhalpaktal, and Urda. Atyrau and Mangystau regions showed similar trends, with frost period reductions of up to 14 days in Atyrau and up to 22 days in Mangystau, notably at MS Akkuduk, Kulaly, and Aktau.

The frost period typically begins in late October and ends in early April. Warming trends during the November–March cold season have led to more frequent and prolonged thaw events. In Western Kazakhstan, thaw days increased significantly between 1974 and 2021, particularly in February and March. While November showed decreasing trends at most stations, March showed a consistent rise in thaw days.

Regionally, positive trends in thaw frequency were observed in February across southern Aktobe and Atyrau. Long-duration thaw events (16–30 days) became notably more common, doubling in frequency during the climate change period. For instance, MS Uralsk recorded increases from 4 to 11 events (16–30 days), and MS Chapaevo saw similar increases—from 4 to 7 (16–20 days) and from 7 to 13 (21–30 days). These changes in thaw frequency and duration are illustrated in Fig. 7.

4 Discussion

Minimal flow is closely linked to annual flow, with a strong correlation between these parameters (Vasil'ev et al. 2020). The variability of minimal streamflow is primarily influenced by meteorological factors, including precipitation, air temperature, humidity, and evapotranspiration (Komlev 2002). Low-flow periods are governed by season-specific conditions: winter low-flow is influenced by the duration and intensity of sub-zero temperatures, while summer-autumn low-flow depends largely on precipitation and groundwater supply (Alekseevskij et al. 2012).

Studies consistently confirm that the duration and stability of the low-flow period are determined by runoff-forming factors, among which atmospheric precipitation and groundwater recharge are most significant. Notably, not only the current year's precipitation but

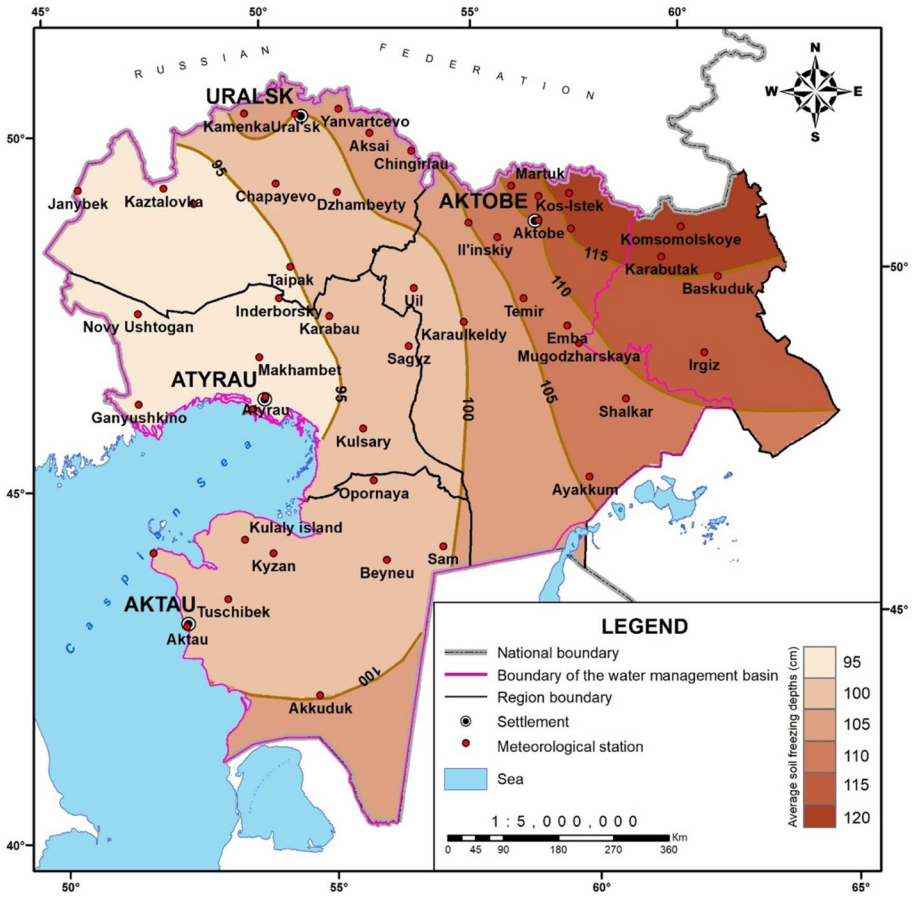


Fig. 5 Average soil freeze depths (cm) of the Zhaiyk-Caspian water management basin for the period 1974–2021

also that of the preceding 2–3 years plays a crucial role in shaping the groundwater component of streamflow (Sivokhip et al. 2018).

In the Zhaiyk-Caspian WMB, recent changes in summer-autumn runoff are complex and not uniform across the basin. A key trend identified in plain rivers of Kazakhstan is the reduction in the contribution of spring runoff and an increase in runoff during low-water periods. This shift leads to a flattening of the annual hydrograph, as reported in several studies (Bolgov et al. 2014; Dzhamalov et al. 2015). The dominant driver behind this transformation is a long-term increase in winter air temperatures, which has elevated the frequency of thaws and enhanced winter runoff, in line with conclusions by Dzhamalov et al. (2017) and Moldakhmetov et al. (2020).

Water generated during thaw events primarily increases soil moisture in the active layer, thereby improving conditions for infiltration and contributing to sustained groundwater recharge and rising low-flow river discharges (Sosnovskij and Osokin 2019). In addition to thaw dynamics, winter runoff is also significantly affected by soil freezing depth, which is itself determined by the sum of negative average daily temperatures over the cold season. A

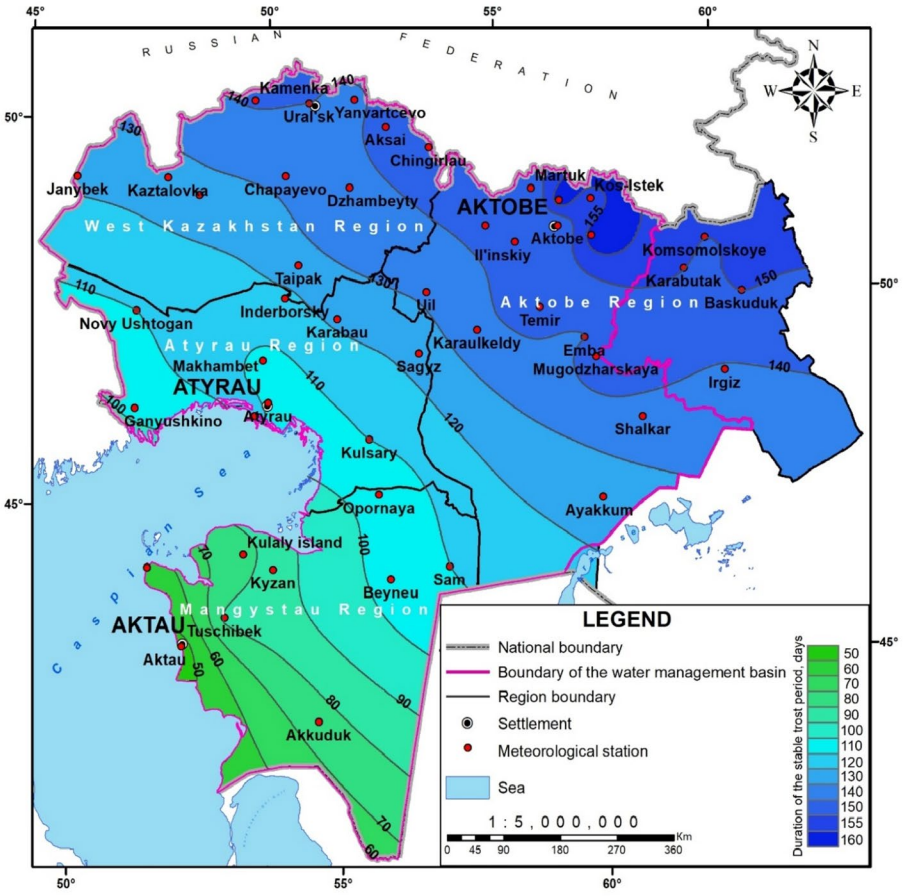


Fig. 6 Duration of the stable frost period in the Zhaiyk-Caspian water management basin for the period 1974–2021

shorter duration of sub-zero temperatures leads to reduced frost penetration in the soil, thus facilitating groundwater movement.

Based on long-term soil freezing data for the Zhaiyk-Caspian WMB, the authors confirm that climate warming since 1974 has resulted in a noticeable decline in soil freezing depth. This trend is directly linked to increased winter temperatures, more frequent thaw events, and a shortening of the cold season, all of which have contributed to higher winter runoff (Kalyuzhny and Lavrov 2016).

In both winter and summer, temperature regimes are the dominant factor influencing the transition from minimum flow to complete flow cessation. In winter, extremely low air temperatures cause deep soil freezing and the formation of stable ice cover, often leading to a sharp reduction or total suspension of runoff. In summer, flow cessation is generally caused by the depletion of groundwater reserves. Consequently, flow resumption depends on the occurrence of runoff-generating precipitation in summer or a shift to above-freezing air temperatures in winter (Vladimirov 2008; Galperin et al. 2016).

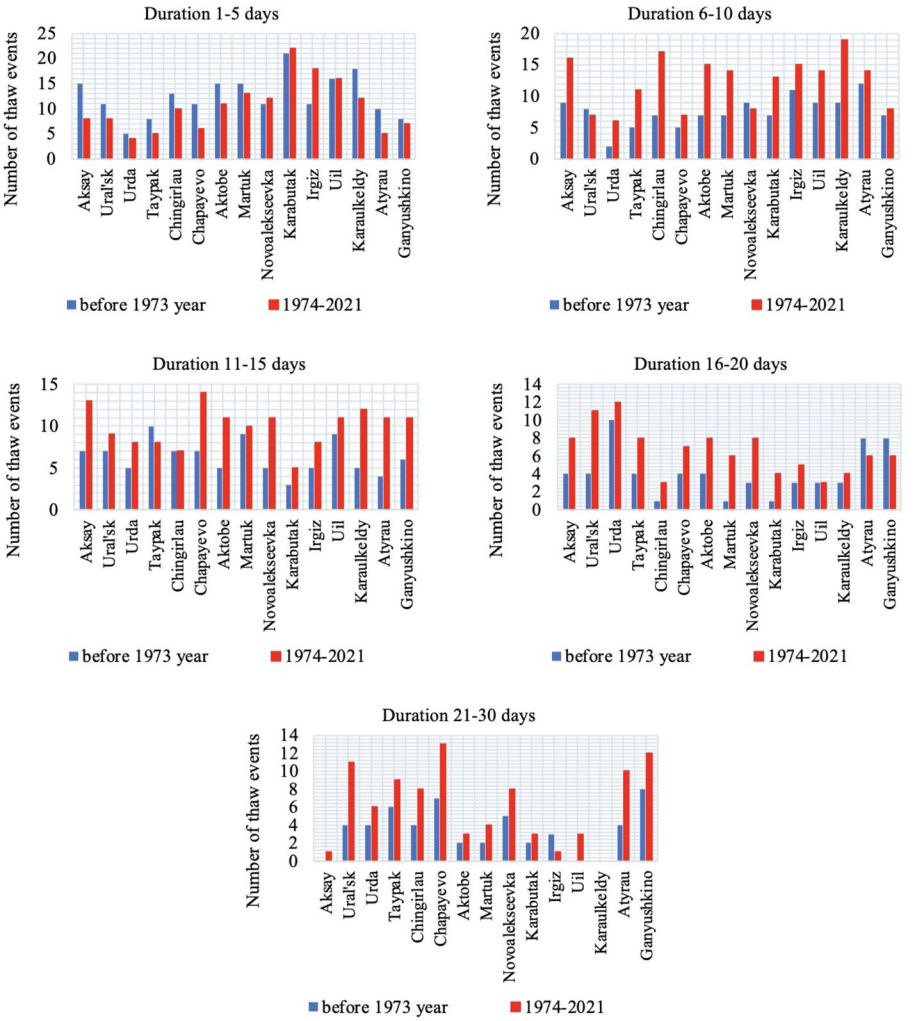


Fig. 7 Number of thaw events of different durations at meteorological stations in the Zhaiyk-Caspian water management basin

Overall, the study findings indicate a clear trend of rising air temperatures in the basin, significantly altering intra-annual runoff dynamics. These results provide a robust foundation for future research, including scenario-based forecasting of minimal runoff under projected climate change conditions.

5 Conclusions

A comprehensive analysis was conducted to identify the key climatic factors influencing minimal streamflow in the rivers of the Zhaiyk-Caspian Water Management Basin (WMB). The results demonstrate that changes in precipitation and temperature regimes have a substantial impact on minimum discharge patterns across the basin.

The assessment of streamflow characteristics reveals widespread increases in minimum flow, largely driven by climatic factors. During the summer-autumn low-flow period, some rivers—such as the Zhem and Temir—experienced reductions in minimal mean monthly discharge of up to 37%. In contrast, other rivers, including the Elek, Or, and Shagan, recorded increases of up to 2.6 times. Over the modern climate change period, the average air temperature during this season increased by approximately 1 °C, while precipitation decreased by up to 15%.

In addition to changes in discharge magnitude, the duration of the low-flow period has extended by as much as 20 days in rivers such as the Elek and Kargaly. The frequency of zero-flow conditions has also increased markedly, reaching 98–100% in several river sections. During the winter low-flow period, an overall increase in minimal flow was observed, coinciding with reductions in negative mean daily air temperatures (by 15–20%) and average soil freezing depth (by approximately 9%). Despite these increases, the frequency of zero winter flow also rose in some rivers—most notably in the Derkul River, where it reached 98%.

The observed increase in winter minimal flow is largely attributed to the rise in frequency and duration of thaw events. The number of thaw episodes lasting 10–30 days increased by 2 to 6 times during the climate change period. These thaws contribute to increased soil moisture, which enhances infiltration and groundwater recharge, ultimately sustaining winter streamflow. Reduced soil freezing, in combination with enhanced subsurface flow contributions, further supports this trend. Moreover, increased winter recharge is thought to augment groundwater storage, which contributes to improved summer-autumn baseflow in some river systems. These findings are consistent with earlier studies (Bolgov et al. 2014; Danilovich et al. 2023; Georgiadi and Groisman 2023).

Conversely, decreases in minimal mean monthly runoff during the summer-autumn period are primarily attributed to elevated air temperatures and reduced precipitation, which limit groundwater recharge and runoff generation. The shortening of the cold season and increased thaw frequency have also diminished the duration and severity of sub-zero conditions, leading to a decline in soil freezing depth. Long-term observations confirm that regional climate warming has caused a sustained reduction in frost depth, which correlates with the observed increase in winter discharge.

The findings of this study have important practical implications for the development of sustainable water resource management strategies. They provide a basis for designing adaptive measures aimed at reducing the risk of hydrological drought and ensuring the resilience of water systems in the Zhaiyk-Caspian WMB under changing climatic conditions.

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Declarations

Ethical Approval This work has not been published or submitted elsewhere.

Consent for Publication The authors consent to publication upon acceptance.

Consent to Participate All authors have read and approved the manuscript and accept full responsibility for its content.

Conflict of interests The authors declare no relevant financial or non-financial interests.

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