

Article

Seasonally Contrasting Sensitivity of Minimal River Runoff to Future Climate Change in Western Kazakhstan: A CMIP6 Scenario Analysis

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Abstract

This study presents a scenario-based assessment of the future sensitivity of minimal low-water runoff to climate change in Western Kazakhstan. An ensemble of global climate models from the Coupled Model Intercomparison Project Phase 6 (CMIP6), combined with dynamically downscaled projections for Central Asia, was applied to estimate minimal monthly runoff during the summer–autumn and winter low-water periods for the rivers of the Zhaiyk–Caspian water management basin. The analysis covers three future time horizons: 2040 (2031–2050), 2060 (2051–2070), and 2080 (2071–2090), under two greenhouse gas concentration scenarios: SSP3-7.0 (moderately high emissions) and SSP5-8.5 (high emissions). The results reveal a pronounced seasonal contrast in the projected hydrological response. During the winter low-water period, a steady increase in minimal runoff is projected for all rivers, with the most significant changes observed for the Or, Zhem, Temir, and Shagan rivers. This increase is primarily driven by higher winter precipitation, increased thaw frequency, and enhanced infiltration recharge. Conversely, despite modest increases in summer–autumn precipitation, minimal runoff during the summer–autumn low-water period is projected to decline significantly, particularly in the southern basins, due to elevated evapotranspiration rates and soil moisture deficits associated with rising air temperatures. These findings emphasize the importance of developing seasonally differentiated, climate-resilient water management strategies to mitigate low-flow risks and ensure water security under future climate conditions in arid and semi-arid regions.

Keywords: minimal runoff; seasonal hydrological response; climate change; CMIP6; Western Kazakhstan; water resource management



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1. Introduction

Uncertainty regarding the evolution of natural and climatic conditions remains one of the most critical challenges for environmental and water resource management today. The impacts of climate change on freshwater systems have been extensively addressed in international scientific forums and high-level reports, including those by the United Nations (UN), the World Meteorological Organization (WMO), and the Intergovernmental

Panel on Climate Change (IPCC). The latest IPCC assessment highlights the urgent need for adaptation measures, as the adverse effects of the ongoing climate crisis are already evident across multiple regions [1].

While the causes of the observed warming over recent decades result from both natural variability and anthropogenic greenhouse gas emissions, the hydrological implications are evident. Climate change directly or indirectly alters river regimes, affecting water availability and contributing to the increased frequency of extreme hydrological events, such as floods, droughts, and low-flow periods [2,3].

Modern hydrological and water management challenges driven by ongoing climate change require not only solid theoretical foundations but also the development of advanced methods and approaches to addressing these challenges under non-stationary hydrological conditions. The need to establish methodological principles for solving contemporary engineering hydrology problems highlights the importance of creating tools that enable quantitative assessments and reliable forecasts of river flow under changing climatic and environmental conditions.

Scenario-based forecasting of minimum river discharge using the sixth phase of the Coupled Model Intercomparison Project (CMIP6) models represents a key direction in hydrological research, particularly in the context of observed and projected changes in climatic variables. Improving our understanding of potential changes in minimum river flow within the study area is essential for developing effective water resource management strategies and strengthening adaptation to climate change.

In this context, the development of improved methodologies for characterizing and forecasting water resources under non-stationary climate conditions has become essential [4,5]. Accurate determination of river flow parameters, particularly during critical low-flow periods, is fundamental for water resource planning, infrastructure design, and risk management, especially in regions with uneven water distribution and high water demand [6].

The present study constitutes the second phase of a previously conducted research effort [7], which provided a contemporary assessment of observed changes in minimal river runoff during the summer–autumn and winter low-water seasons for the period 1974–2021. The objective of this study is to develop a long-term, scenario-based projection of minimal river runoff for the summer–autumn and winter low-water periods in the rivers of the Zhaiyk–Caspian water management basin, located in the western region of Kazakhstan, using CMIP6 scenarios that account for projected future climate change.

To achieve this objective, several specific tasks were undertaken. First, an analysis of climatic predictors—including air temperature and atmospheric precipitation—was conducted to assess their influence on minimal river runoff in the Zhaiyk–Caspian water management basin. A key component of the study also involved the selection and justification of CMIP6 models that most accurately capture potential future climate changes in Western Kazakhstan, considering regional climate sensitivity. Based on the selected models, scenario-based projections of minimal runoff for the basin's rivers were developed for the SSP3-7.0 (moderately high emissions) and SSP5-8.5 (high emissions) scenarios for the time horizons of 2040 (2031–2050), 2060 (2051–2070), and 2080 (2071–2090). These projections provide a scientific basis for assessing potential changes in water resources under future climate change conditions.

2. Materials and Methods

2.1. Study Area

Western Kazakhstan is one of the largest economic and geographical regions of the Republic of Kazakhstan by area and is located at the intersection of Eastern Europe and

Central Asia. It comprises four oblasts: Aktope, West Kazakhstan, Atyrau, and Mangystau, which together encompass 36 administrative districts. The region shares borders with Russia to the north and Uzbekistan and Turkmenistan to the south; it opens onto the Caspian Sea to the west and is adjacent to other Kazakh oblasts to the east.

Extending from the eastern edge of the Volga River delta in the west to the Turan Lowland in the southeast, and from the southern foothills of the Ural Mountains and the Obshchii Syrt to the Ustyurt Plateau, the region covers a total area of 736,241 km², with a north–south length of approximately 1200 km and an east–west extent of about 1300 km. The Mugaldzhar Ridge, which rises 200–300 m above the Zhaiyk-Zhem Plateau, serves as the watershed dividing Western and Central Kazakhstan and constitutes the source region for the area’s main rivers: the Oiyl, Zhem, Elek, Or, and others. The relief is characterized by undulating hilly plains, sand dunes, solonchaks (salt flats), and endorheic depressions. Of particular geographical significance is the Pre-Caspian Lowland, which stretches along the northern coast of the Caspian Sea and is distinguished by its leveled surface, numerous lakes, and salt marshes [8–12] (Figure 1).

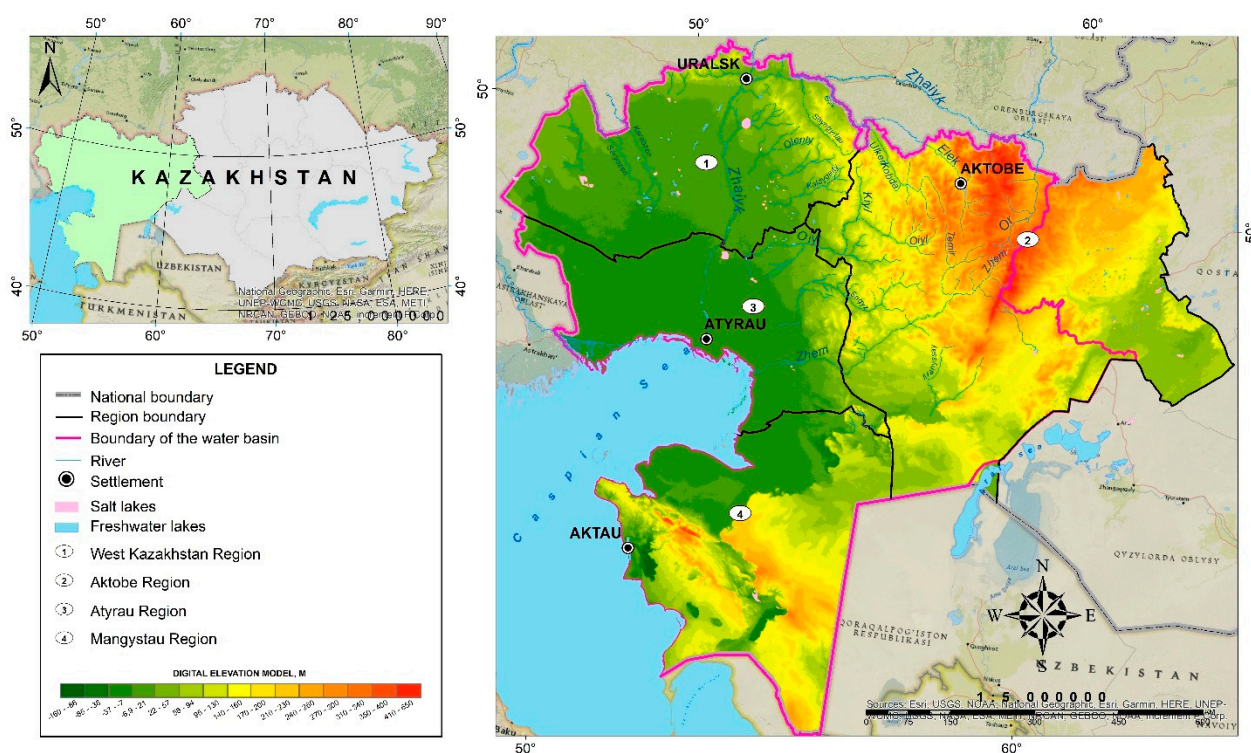


Figure 1. Geographical location of the Zhaiyk–Caspian water management basin in Western Kazakhstan.

The study area is not only the largest in terms of territory but also one of the most economically significant regions of the country due to its extensive oil industry.

The region contains over 1500 rivers and temporary watercourses longer than 10 km, with a total combined length exceeding 45,000 km. The main surface water sources of the region include the northeastern and eastern coasts of the Caspian Sea, as well as the rivers Zhaiyk, Oiyl, Zhem, Sagyz, Elek, Or, Kobda, Shagan, Karaozen, and Saryozen, together with the delta branches of the Volga-Kigach, Sharanovka, and other smaller rivers.

2.2. Source Data

In this study, official meteorological cadastral data from RGP “Kazhydromet” were used to analyze recent changes in climatic characteristics. The analysis utilized records from 40 meteorological stations, including daily air temperature and atmospheric precipita-

tion, covering the long-term period from 1940 to 2021. In addition, data from stationary observations of river discharge for medium-sized rivers within the Zhaiyk–Caspian water management basin were used for both the winter and summer–autumn low-water periods. These discharge data, covering the entire observation period up to and including 2021, were obtained from nine key hydrological posts where runoff during low-water periods is systematically monitored. The hydrological data are available on the official website: <https://www.kazhydromet.kz/ru/gidrologiya/ezhegodnye-dannye-o-rezhime-i-resursah-poverhnostnyh-vod-sushi-eds> (last accessed on 6 July 2025). The list of meteorological stations and hydrological posts used for the calculations and analyses is provided in Tables 1 and 2.

Table 1. Meteorological stations used in the study.

Meteorological Station							
1	Novorossiyskoe	11	Uralsk	21	Temir	31	Akkuduk
2	Aktobe	12	Kamenka	22	Karaulkeldy	32	Kyzan
3	Martuk	13	Chapayevo	23	Uil	33	Tuschibek
4	Rodnikovka	14	Taipak	24	Sagiz	34	Aktau
5	Kos-Istek	15	Makhambet	25	Karabau	35	Fort Shevchenko
6	Il'insky	16	Atyrau	26	Kulsary	36	Zhalpaktal
7	Novoalekseevka	17	Dzhambeity	27	Shalkar	37	Dzhanybek
8	Chingirlau	18	Karatobe	28	Ayakkum	38	Urda
9	Aksai	19	Mugodzharskaya	29	Beineu	39	Novy Ushtogan
10	Yanvartsevo	20	Emba	30	Sam	40	Ganyushkino

Table 2. Hydrological posts used in the study.

N°	Hydrological Post	Watershed Area (km ²)	Average Height of the Basin, (m)
1	Or-Bogetsay	7480	350
2	Elek-Aktobe	11,000	340
3	Kargaly-Kargaly	5000	370
4	Ulken Kobda-Kobda	8110	240
5	Karakobda-Alpasay	2240	270
6	Shagan-Kamenny	4000	130
7	Zhem-Zharkamys	26,000	260
8	Temir-Leninski	5310	280
9	Oiyl-Taltogay	17,000	200

Based on geographic system analysis, which considers both zonal and azonal factors, as well as orography, river basins, and atmospheric circulation, the region is divided into the following hydrologically homogeneous areas (Figure 2):

- I—Left-bank tributaries of the Zhaiyk River: Or, Elek, Ulken Kobda, Shyngyrlau;
- II—Right-bank tributaries of the Zhaiyk River: Embulatovka, Rubezhka, Shagan, Derkul; rivers of the western part of Obschiy Syrt not flowing into the Zhaiyk River: Shyzhyn 1st, Shyzhyn 2nd, Karaozen, Saryozen;
- III—Zhaiyk River;
- IV—Rivers of the eastern part of the Caspian Lowland not flowing into the Zhaiyk River: Olenty, Kuperanakty, Buldurty, Shiderty;
- V—Southern rivers: Oiyl, Sagyz, Zhem;
- VI—Arheic area;
- VII—Arheic area.

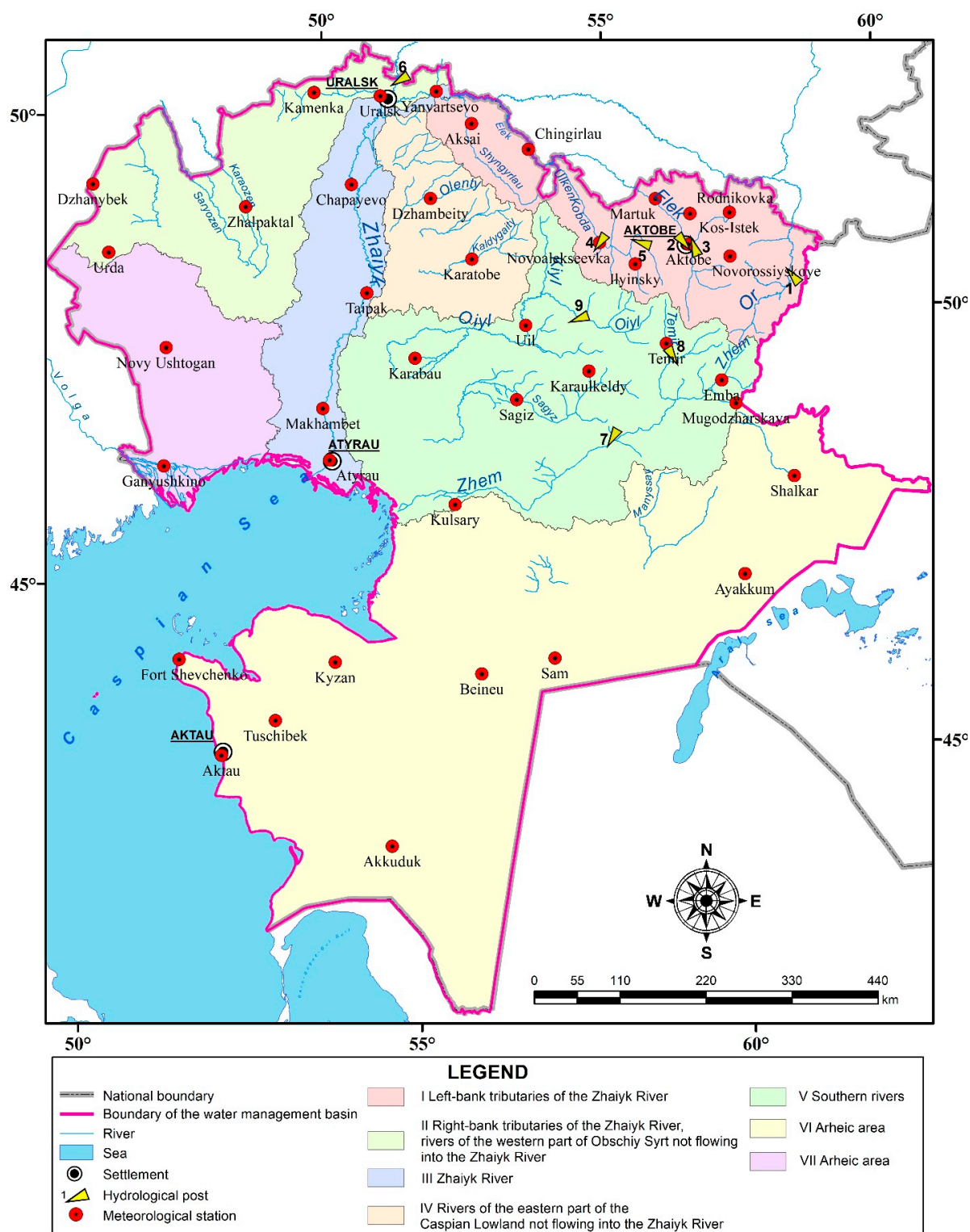


Figure 2. Location of meteorological stations and hydrological posts within the Zhaiyk–Caspian water management basin in relation to hydrologically homogeneous areas.

The hydrological information used in this study included data on average monthly water discharges for the summer–autumn and winter seasons. The summer–autumn season was defined as the period from June to November, with the lowest monthly runoff within this period considered as the minimal average monthly runoff for the summer–autumn low-water period. The winter season was defined as the period from December to February,

with the lowest monthly runoff during this period considered as the minimal average monthly runoff for the winter low-water period.

In addition to the observational dataset, forecasted values of climatic characteristics from CMIP6 models were used to develop long-term scenario-based projections of water resources under various future climatic and socioeconomic conditions. The forecasted climatic variables were obtained from the online resource: <https://www.isimip.org/> (last accessed on 6 July 2025). Within the ISIMIP projection framework, forecasted climate data were applied for two socioeconomic development scenarios: SSP3-7.0 (moderately high emissions) and SSP5-8.5 (high emissions), extending up to the year 2100. This approach enables the assessment of a wide range of possible future conditions and facilitates the evaluation of climate risks while accounting for uncertainty.

2.3. Methods

To identify relationships between minimal runoff and the climatic factors influencing it, an analysis was conducted on the dynamics of streamflow-forming climatic characteristics within the basin. The study examined long-term series of precipitation sums for the summer–autumn (June–November), autumn (September–October), and winter (December–February) seasons; long-term series of average monthly air temperatures for the summer–autumn (June–November) and winter (December–February) seasons; long-term series of cumulative negative (November–March) and positive (December–March) air temperatures; and the number of days with above-zero air temperatures during the cold season.

The statistical significance of the linear trend was determined in accordance with the recommendations of Rozhdestvensky and Lobanova [13]. It is proposed to reduce the assessment of trend significance to the evaluation of the correlation coefficient (R) for the dependence $Y = f(t)$, where Y is the studied characteristic and t is time. The trend is considered statistically significant if the following condition is met (Equation (1)):

$$\frac{R}{\sigma_R} \geq S \quad (1)$$

where R is the correlation coefficient, σ_R is the random root-mean-square error. At a 5% significance level or at a 95% confidence limit, $S = 2$.

Scenario-based forecasts of minimal runoff for the summer–autumn and winter low-water periods were developed based on established relationships between minimal runoff and meteorological characteristics for the baseline period, considering two scenarios: SSP3-7.0 (a scenario of a fragmented world with high regional risks) and SSP5-8.5 (a scenario of intensified economic growth with maximum emissions) for the years 2040, 2060, and 2080. The forecasts are based on global CMIP6 models from the ISIMIP projection. The ISIMIP project provides regional climate modelling results for Central Asia based on CMIP6 scenarios, using dynamic downscaling techniques [14]. The models were calibrated to account for regional characteristics, thereby improving the accuracy of climate risk assessments and supporting adaptive decision-making processes.

Dynamic downscaling of global climate models (GCMs) is a key approach to enhancing the accuracy of regional climate projections in areas with complex orography and high spatial heterogeneity. This method is particularly important for accurately reproducing extreme precipitation events, which are highly sensitive to terrain and atmospheric thermodynamics. Despite certain uncertainties, dynamic downscaling provides physically based and spatially detailed climate data essential for regional impact assessments.

In this study, a targeted selection of climate models from the CMIP6 project was carried out for forecasting purposes. Models developed by leading climate research centres were selected: GFDL (USA), MRI (Japan), MPI (Germany), IPSL (France), and UKESM

(United Kingdom). This approach ensures the formation of a representative ensemble that accounts for differences in the parameterization of atmospheric processes, circulation patterns, and interactions between components of the climate system, thereby covering a wide range of climate sensitivities: GFDL-ESM4, IPSL-CM6A-LR, and MPI-ESM1-2-HR, which are characterized by low climate sensitivity, and MRI-ESM2-0 and UKESM1-0-LL, which are models with high climate sensitivity [15]. The models were selected based on their structural independence, proven reliability in reproducing climate processes, and consistency with previous phases of the ISIMIP project. This limited yet representative set of models allows for a balance between projection accuracy and computational efficiency, avoiding the need to utilize the entire CMIP6 ensemble [16].

The criteria for forecast applicability were determined in accordance with [17]. The ratio $\bar{S}/\bar{\sigma}$ is used as an empirical criterion for both the applicability and quality of the forecasting method. The accuracy of the forecasting method is assessed using the root-mean-square error of the verification forecasts, calculated by the following formula:

$$S = \sqrt{\frac{\sum_{i=1}^n (y_i - y'_i)^2}{n - m}} \quad (2)$$

where y_i and y'_i are the observed and predicted values, respectively;

n is the number of observations in the series;

m is the number of degrees of freedom, equal to the number of constants in the predictive equation.

The standard deviation of the predicted variable from its mean is calculated as:

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n - 1}} \quad (3)$$

where y_i is the predicted value of the variable, $\bar{y}$ is its mean value, and n is the number of observations in the series.

Depending on the number of observations, the following conditions determine the applicability of the forecasting method (Table 3).

Table 3. Applicability criteria for forecasting methods.

Condition	Applicability Criteria
$n \leq 15$	$S/\sigma \leq 0.70$
$15 < n < 25$	$S/\sigma \leq 0.75$
$n \geq 25$	$S/\sigma \leq 0.80$

The strength of the relationship between the predicted phenomenon and its influencing factors is also characterized by the correlation ratio:

$$\rho = \sqrt{1 - (S/\sigma)^2} \quad (4)$$

For linear relationships, the correlation ratio numerically coincides with the correlation coefficient ($r = \rho$). A decrease in the $\bar{S}/\bar{\sigma}$ ratio or an increase in the ρ value indicates improved forecasting accuracy. The quality of the method is assessed based on the values of $\bar{S}/\bar{\sigma}$ or ρ (Table 4).

Table 4. Indicators of forecasting method quality for $n \geq 25$.

Quality Category of the Method	S/σ	ρ
Good	≤ 0.50	≥ 0.87
Satisfactory	0.51–0.80	0.86–0.60

3. Results

The magnitude and variability of low-water runoff are determined by multiple factors, with groundwater levels playing a key role. Groundwater levels, in turn, depend on both climatic conditions and the characteristics of the underlying surface [18]. To identify the climatic factors driving changes in minimal runoff, the first stage of the study involved an analysis of statistically significant changes in seasonal precipitation totals and air temperature within the basin over the representative period of 1940–2022.

Table 5 presents the linear trend coefficients for these climatic characteristics in the Zhaiyk–Caspian water management basin, with statistically significant trends highlighted.

Table 5. Coefficients of the linear trends of climatic characteristics for meteorological stations of the Zhaiyk–Caspian water management basin for 1940–2021.

Meteorological Station	ΣP for the Summer–Autumn Low-Water Period (VI–XI), mm/10 Years	T_{avg} for the Summer–Autumn Low-Water Period (VI–XI), °C/10 Years	ΣP for Autumn (IX–X), mm/10 Years	ΣP for Winter (XII–II), mm/10 Years	T_{avg} for Winter (XII–II), °C/10 Years	$\Sigma T+$ for Winter (XII–III), °C/10 Years	N° of Days with T+ in the Winter Season (XII–III), Days/10 Years	$\Sigma T-$ for the Cold Period (XI–III), mm/10 Years
Novorossiyskoye	−3.5	0.2	−1.8	6.7	0.4	1.0	0.4	55
Aktobe	−0.2	0.3	−1.1	7.6	0.5	2.2	0.8	67
Martuk	−2.0	0.2	−1.1	7.6	0.5	1.7	0.7	64
Rodnikovka	−8.6	0.2	−4.2	4.1	0.4	0.7	0.3	55
Kos-Istek	−7.1	0.2	−3.1	5.1	0.3	1.6	0.6	38
Ilyinsky	−7.3	0.3	−4.0	−1.2	0.5	2.6	0.6	54
Novoalekseevka	3.6	0.2	−2.9	7.1	0.5	2.1	0.8	56
Chingirlau	−4.5	0.3	−2.1	4.1	0.4	2.1	0.8	50
Aksai	−1.4	0.3	−1.2	5.6	0.5	3.1	1.1	70
Yanvartsevo	−2.3	0.3	−0.4	4.7	0.4	3.7	1.3	59
Uralsk	0.3	0.3	0.0	3.5	0.5	4.3	1.6	68
Kamenka	−4.6	0.3	0.2	−1.2	0.4	3.5	1.0	56
Chapayevo	−2.5	0.4	−1.2	0.4	0.5	5.3	1.8	68
Taipak	−3.5	0.3	−1.5	2.3	0.5	7.1	2.3	66
Makhambet	2.1	0.5	0.8	2.0	0.8	14.3	4.3	79
Atyrau	−1.2	0.3	0.0	1.4	0.5	11.5	3.0	58
Dzhambeity	−3.0	0.3	−1.6	1.8	0.5	3.3	1.2	64
Karatobe	−2.4	0.3	−1.6	2.0	0.5	4.9	1.6	65
Mugodzharskaya	−3.3	0.2	−2.8	3.8	0.4	2.6	2.6	51
Emba	−1.6	0.2	−1.9	1.9	0.4	2.2	0.5	46
Temir	−3.1	0.2	−2.7	4.8	0.5	3.1	0.9	64
Karaulkeldy	−0.2	0.3	−1.2	3.7	0.4	3.7	0.9	54
Uil	−1.8	0.1	−1.4	2.7	0.2	1.1	0.1	22
Sagiz	−4.2	0.2	−2.3	0.2	0.5	5.9	1.8	47
Karabau	−1.7	0.3	−1.1	1.0	0.6	8.0	2.5	69
Kulsary	−3.7	0.4	−3.3	1.1	0.7	16.9	4.3	75
Shalkar	−1.0	0.2	−1.3	1.4	0.3	6.6	1.4	46
Ayakum	−2.1	0.3	−1.9	−0.3	0.4	9.5	1.7	49
Beineu	−4.5	0.3	−2.5	−0.4	0.4	17.4	3.4	44
Sam	0.3	0.3	−1.0	2.9	0.3	12.9	2.1	27
Akkuduk	0.2	0.3	0.5	−0.3	0.3	20.5	3.3	32
Kyzan	−5.2	0.4	−1.6	0.0	0.4	20.2	4.1	37
Tuschibek	−1.8	0.3	−1.1	0.0	0.2	15.8	3.3	25
Aktau	3.4	0.6	−0.7	1.0	0.4	29.2	3.7	14
Fort	−2.3	0.4	−1.3	−0.2	0.5	37.6	6.1	24
Shevchenko	−2.5	0.3	0.9	2.9	0.6	7.0	2.4	72
Zhalpaktal	0.1	0.3	1.9	1.7	0.6	9.6	2.9	77
Urd	−0.8	0.3	1.6	5.4	0.5	10.9	3.1	60
Novy	−0.6	0.3	0.1	1.4	0.5	13.5	3.6	62
Ushtogan	−2.3	0.2	−1.2	−1.0	0.5	12.7	3.2	46

Note: P—atmospheric precipitation, T—air temperature; statistically significant trends are written in bold.

An analysis of changes in summer–autumn precipitation totals revealed a general decreasing trend across most of the study area, though these trends are statistically insignif-

icant. The linear trend coefficient for precipitation at the Rodnikovka meteorological station (northwest) is -8.6 mm per decade; at the Mugodzhar meteorological station (Mugodzhar Mountains), it is -3.3 mm per decade; at the Zhalpaktal meteorological station (west of the basin), it is -2.5 mm per decade; and at the Kyzan meteorological station (south of the basin), it is -5.2 mm per decade. However, several meteorological stations exhibit only a weak positive trend, including Novoalekseevka, Uralsk, Makhambet, Aktau, Dzhanibek, and Akkuduk (Figure 3).

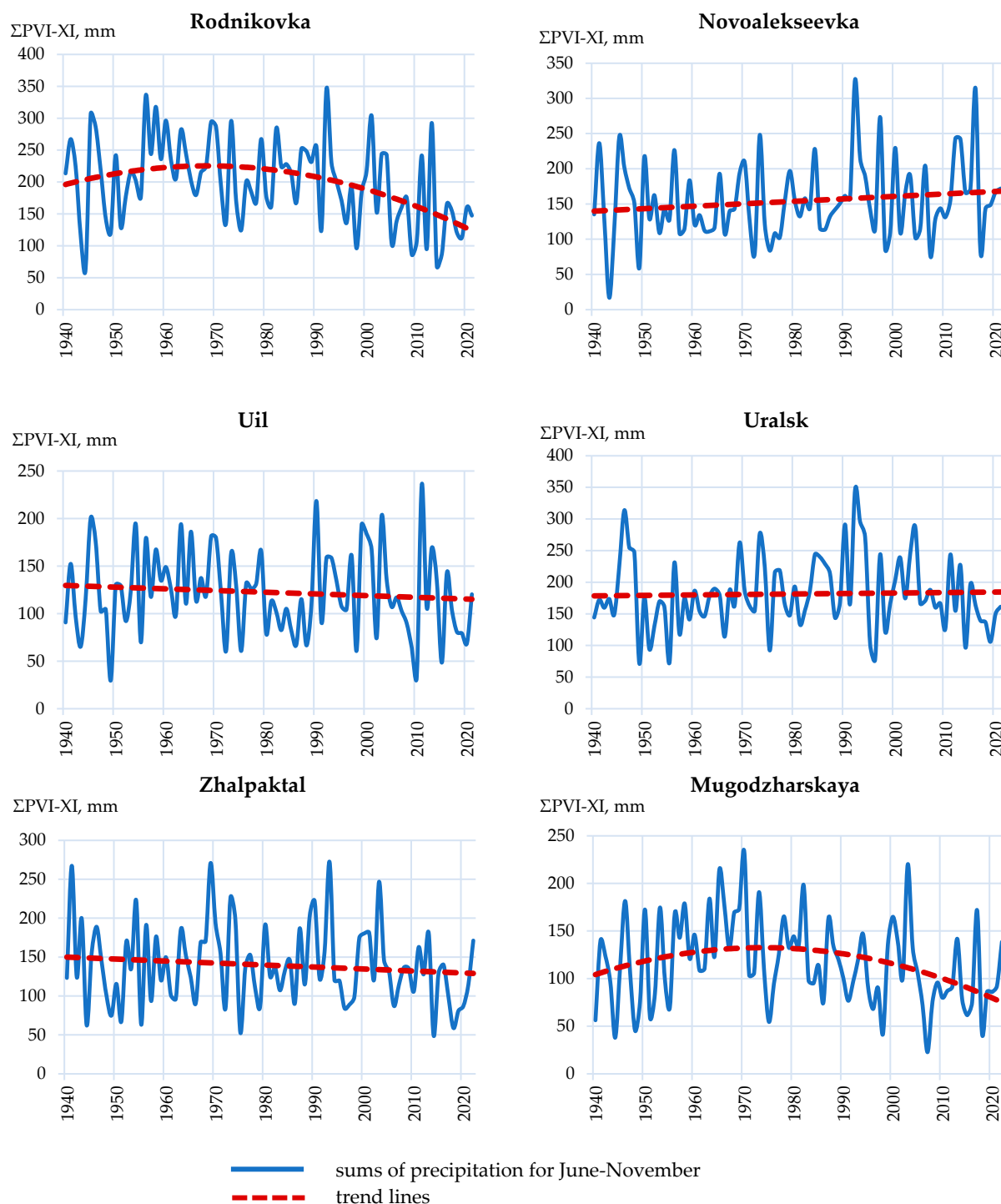


Figure 3. Long-term changes in sums of atmospheric precipitation during the summer–autumn season for meteorological stations of the Zhaiyk–Caspian water management basin.

Thus, summer–autumn precipitation totals alone cannot explain the observed changes in minimal summer–autumn runoff. In addition to precipitation, air temperature during this season should also be taken into account. An analysis of changes in air temperature during the summer–autumn low-water period revealed a significant and widespread increase in average air temperatures across the entire basin. The warming trend is statistically significant and intensifies from the north to the south.

The coefficients of the linear trend for average air temperature range from 0.2 to 0.3 °C per decade in the northern, northeastern, and western regions, as well as along the northern coast of the Caspian Sea. In the central part of the basin, this value increases to 0.5 °C per decade. The most pronounced warming is observed in the southern part of the basin and along the eastern coast of the Caspian Sea, where the trend reaches up to 0.6 °C per decade. The most pronounced increase in average air temperature across the basin has been observed since the mid-2000s. Approximately from the same period, a slight decrease in summer–autumn precipitation sums has also been recorded.

During the winter low-flow period, autumn precipitation is the primary source of groundwater recharge. Among the climatic factors influencing the formation of groundwater, the most significant role is attributed to atmospheric precipitation of the current or preceding month, season, year, or even longer period [19]. However, the analysis showed that the linear trend coefficients of autumn precipitation sums are statistically insignificant for most of the meteorological stations. In the majority of the study area, the trend is negative, with magnitudes not exceeding −4.2 mm per decade, as recorded at the Rodnikovka station. At several meteorological stations in the western part of the basin, small positive trends of up to 1.9 mm per decade are observed, such as at the Dzhaniybek station.

This suggests that autumn precipitation alone cannot be considered the primary cause of the observed increase in minimal runoff of winter low flow; however, completely disregarding it would also be a mistake as it contributes to soil moisture recharge prior to the onset of the cold season.

In contrast to the autumn season, long-term winter precipitation sums indicate an overall increase across most of the basin, although significant spatial differences are observed. Statistically significant positive linear trends in winter precipitation, reaching up to 7.6 mm per decade, were recorded at meteorological stations in the northern part of the basin, including Aktobe and Martuk. An exception is the Ilyinsky station, which shows a slight negative trend of −1.2 mm per decade. In the eastern part of the basin, within the Mugodzhary Mountains, linear trend coefficients for winter precipitation reach 4.8 mm per decade, as observed at Temir station.

In contrast, weak positive trends, not exceeding 2.9 mm per decade, are recorded in the central part of the basin, along the Caspian Sea coast, and in endorheic areas, such as at the Sam station. Negative trends in winter precipitation were observed at the Ayakkum, Beineu, Akkuduk, Fort Shevchenko, and Ganyushkino stations. In the western part of the basin, winter precipitation increases range from 1.4 to 5.4 mm per decade, with statistically significant trends recorded at the Urda and Zhalspaktal meteorological stations (Figure 4).

Thaws can also play an important role in the formation of winter runoff, provided they occur with sufficient frequency and duration—a characteristic feature of the study region. To analyse changes in the thaw regime during the winter season, long-term air temperature data were evaluated.

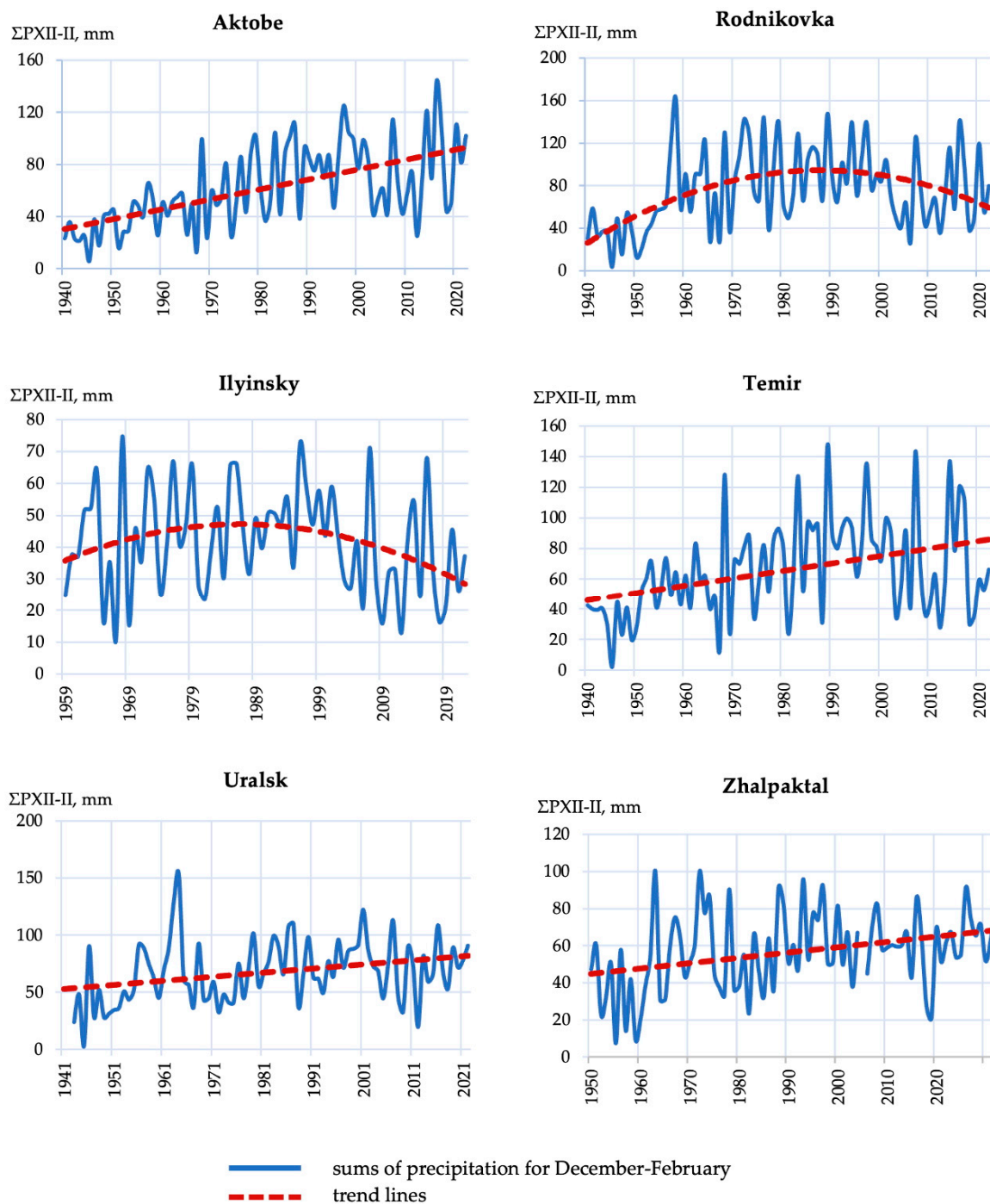


Figure 4. Long-term changes in sums of atmospheric precipitation during the winter season for meteorological stations of the Zhaiyk–Caspian water management basin.

In terms of winter air temperature, a statistically significant increase has been recorded at all meteorological stations across the basin. The intensity of warming increases from the northeast to the southwest, with the most pronounced warming observed along the northeastern coast of the Caspian Sea, reaching up to 0.8 °C per decade at the Makhambet station. The linear trend coefficients in the northeastern part of the basin range from 0.3 °C per decade at the Kosistek station to 0.5 °C per decade at stations such as Aktobe, Novoalekseevka, Temir, and others (Figure 5).

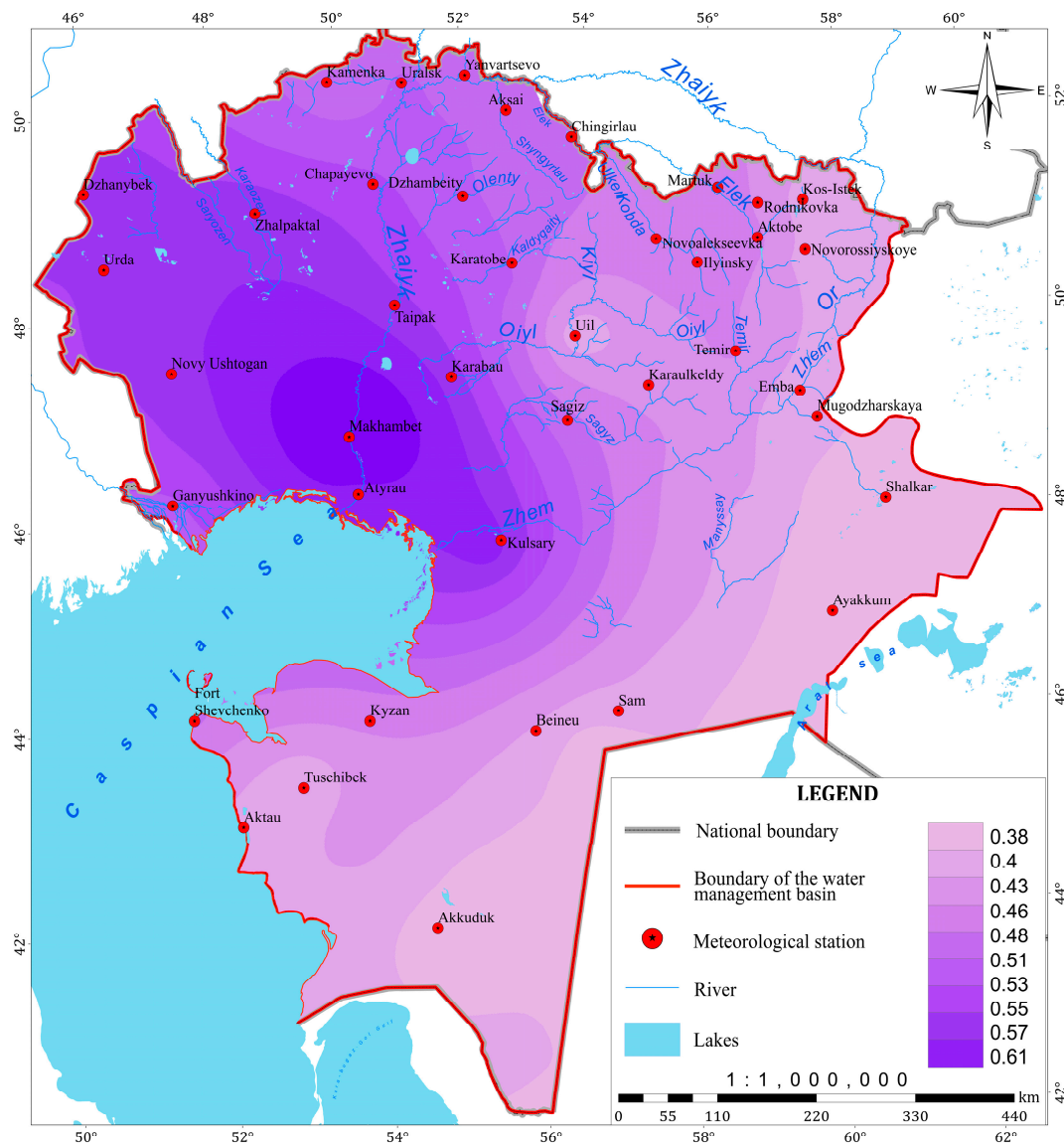
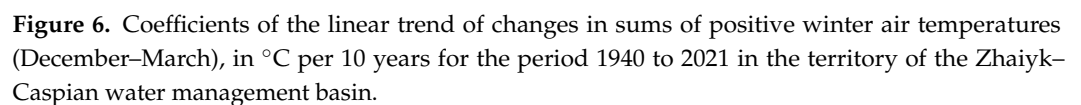


Figure 5. Coefficients of the linear trend of winter air temperature (December–February), in °C per 10 years for the period 1940 to 2021 in the territory of the Zhaiyk–Caspian water management basin.

The sums of positive temperatures and the number of days with positive average daily temperature during the winter period also show a pronounced increase across the entire territory of the studied basin (Figures 6 and 7). As a result, both the frequency and duration of thaw events are increasing. The observed trends are mostly statistically significant throughout the entire study area, with the maximum values recorded in the southern part of the basin (MS Akkuduk, Beineu, Kyzan, Tushchibek) and along the coast of the Caspian Sea (MS Fort Shevchenko, Aktau, Atyrau), where the sum of positive temperatures reaches up to 36.6 °C per decade and the duration of thaw periods increases by up to 6 days per decade.

In the northeastern direction, the intensity of temperature changes decreases, reaching 0.8 °C per decade in the central part of the basin and 0.3 °C per decade in the Mugodzhars Mountains area. A similar decreasing pattern is observed for the duration of positive temperature days, amounting to 2–4 days per decade in the central part of the basin, 0–1 day per decade in the northern part, and 0–3 days per decade in the northeastern region of the basin.



Atmospheric precipitation and air temperature during the summer–autumn period are identified as the key climatic factors governing the magnitude of minimal summer–autumn runoff.

The observed increase in minimal winter runoff is presumably associated with enhanced infiltration recharge of the soil layer, driven by the increased frequency and duration of thaw events, as well as a rise in winter precipitation.

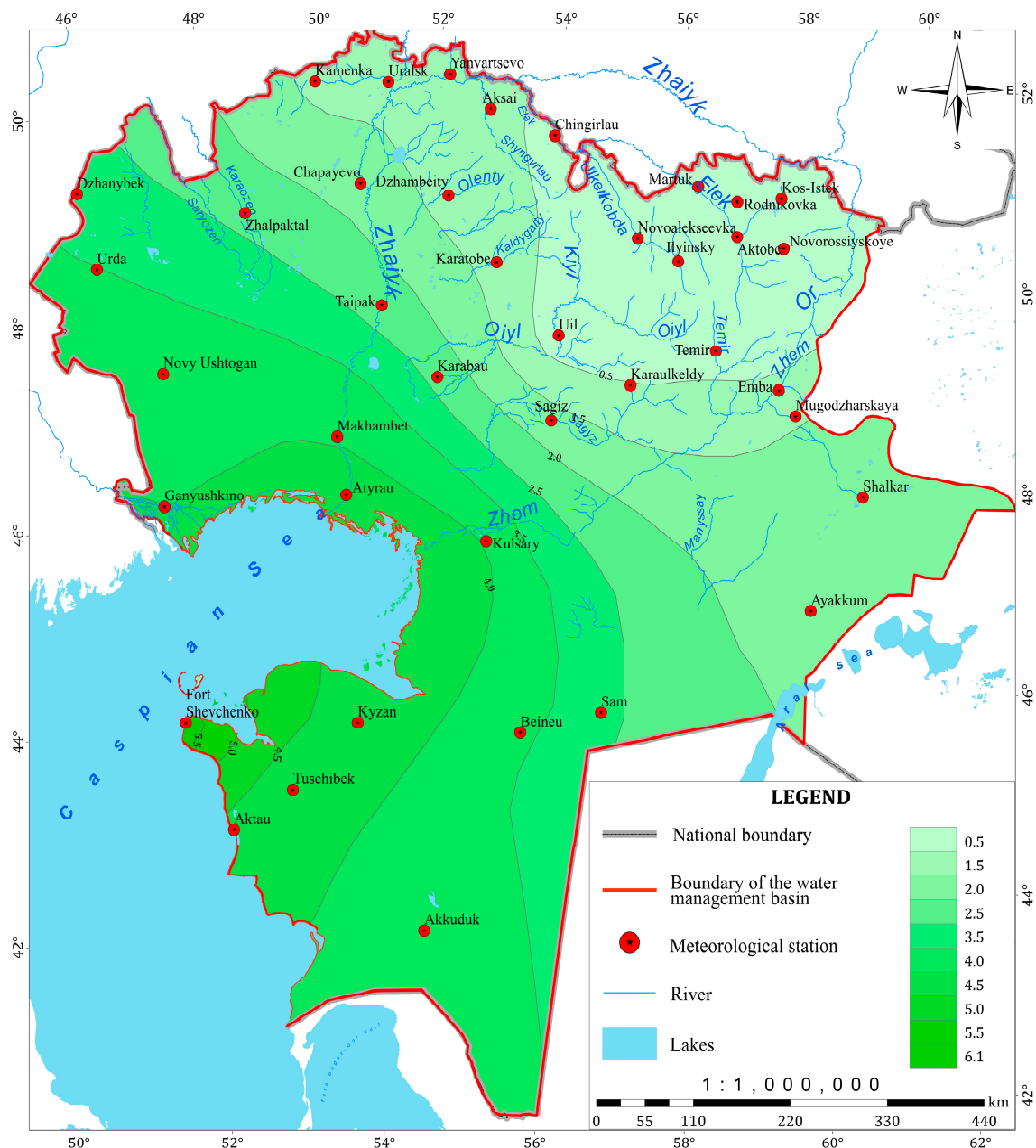


Figure 7. Coefficients of the linear trend of changes in the number of days with positive average daily air temperature during the winter season (December–March), days per 10 years for the period 1940 to 2021 in the territory of the Zhaiyk–Caspian water management basin.

3.1. Long-Term Forecast of Minimal Runoff

In the second phase of the study, based on the conducted analysis, seasonal meteorological factors with statistically significant trends were identified—factors that may exert both direct and indirect influence on the dynamics of minimal runoff.

To quantitatively assess the future state of minimal runoff under projected climate change, statistical relationships were established between minimal runoff and predictors (meteorological variables) that influence its magnitude. For the summer–autumn low-flow period, atmospheric precipitation sums and average air temperatures for the summer–autumn season were selected as predictors. For the winter season, multiple regression models were constructed using the sum of autumn–winter precipitation for the left- and right-bank tributaries of the Zhaiyk River, and the sum of winter precipitation for the

southern rivers of the basin. The average air temperature during the winter months was used as a temperature predictor.

The dependencies were developed for the baseline period 1991–2020, following the new climatological standard normals recommended by the World Meteorological Organization. The calculation scheme for forecasting minimal runoff during the summer–autumn and winter low-water periods is presented in Table 6. The multiple regression correlation coefficients for minimal runoff during the summer–autumn low-water period ranged from $R = 0.60$ to 0.75 , while for the winter low-water period, the coefficients ranged from $R = 0.61$ to 0.71 .

Table 6. Calculation scheme for forecasting the minimal runoff of rivers in the Zhaiyk–Caspian water management basin.

No.	Hydrological Area	River Basin	Calculated Dependencies
Summer–autumn low-water period			
1	Left-bank tributaries of the Zhaiyk River	Or, Elek, Kargaly, Ulken Kobda, Karakobda	$Q_{min} = f(\sum P_{VI-XI}; \bar{T}_{VI-XI})$
2	Right-bank tributaries of the Zhaiyk River	Shagan	$Q_{min} = f(\sum P_{VI-XI}; \bar{T}_{VI-XI})$
3	Southern rivers	Zhem, Temir, Oiyl	$Q_{min} = f(\sum P_{VI-XI}; \bar{T}_{VI-XI})$
Winter low-water period			
1	Left-bank tributaries of the Zhaiyk River	Or	$Q_{min} = f(\sum P_{IX-II}; \bar{T}_{IX-II})$
		Elek, Kargaly	$Q_{min} = f(\sum P_{IX-II}; \bar{T}_{IX-II})$
		Ulken Kobda	$Q_{min} = f(\sum P_{IX-II}; \bar{T}_{IX-II})$
		Karakobda	$Q_{min} = f(\sum P_{IX-II}; \bar{T}_{IX-II})$
2	Right-bank tributaries of the Zhaiyk River	Shagan	$Q_{min} = f(\sum P_{IX-II}; \bar{T}_{IX-II})$
3	Southern rivers	Zhem, Temir, Oiyl	$Q_{min} = f(\sum P_{IX-II}; \bar{T}_{IX-II})$

Note: P—atmospheric precipitation, T—air temperature.

3.2. Projection of Minimal Runoff During the Summer–Autumn Low-Water Period

The scenario-based forecasts of minimal runoff for the summer–autumn and winter low-water periods, developed based on the established statistical relationships, were prepared for two climate development scenarios: SSP3-7.0 (moderately high emissions) and SSP5-8.5 (high emissions) for the years 2040, 2060, and 2080, relative to the baseline period. The results are graphically presented in Figure 8. Seasonal changes in precipitation and air temperature for the Zhaiyk–Caspian water management basin under future climate conditions are provided in Tables 7 and 8.

According to the forecast data for both the SSP3-7.0 and SSP5-8.5 scenarios, a reduction in minimal runoff during the summer–autumn low-water period is expected for most of the left-bank tributaries of the Zhaiyk River, with the exception of the Or River.

For the Elek River and its tributary, the Kargaly River, a significant reduction in runoff is projected under both scenarios. Compared to the baseline period, minimal runoff is expected to decrease by 37–45% under SSP3-7.0 and by 41–47% under SSP5-8.5 by 2040; by 53–56% (SSP3-7.0) and 54–60% (SSP5-8.5) by 2060; and by 59–68% (SSP3-7.0) and 68–74% (SSP5-8.5) by 2080. Runoff in this part of the basin is projected to decline steadily, especially under the more extreme climate scenario, despite an expected increase in summer–autumn precipitation of up to 14% under SSP3-7.0 by 2040, up to 10% under SSP5-8.5 by 2060, and up to 12% under SSP3-7.0 by 2080.

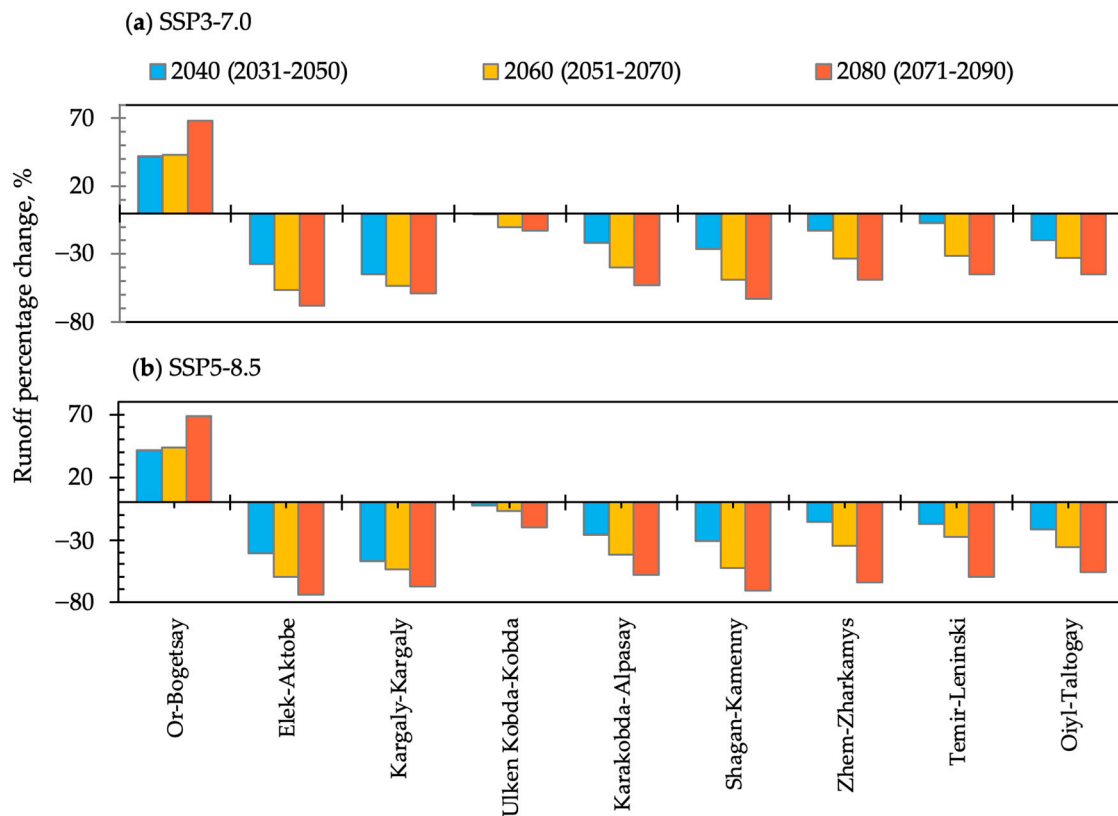


Figure 8. Projected percentage changes in the average monthly minimal runoff of the summer-autumn low-water period of rivers in the Zhaiyk-Caspian water management basin relative to the historical average (1991–2020).

Table 7. Projected changes in summer–autumn season precipitation in the territory of the Zhaiyk-Caspian water management basin.

Hydrological Area	River Basin	Predictor	Base Period (1991–2020)	Future Scenario	2040 (2031–2050)	2060 (2051–2070)	2080 (2071–2090)
			Actual Measured Value, mm		Rate of Change, %	Rate of Change, %	Rate of Change, %
Left-bank tributaries of the Zhaiyk River	Or River basin	ΣP_{VI-XI}	164	SSP3-7.0 SSP5-8.5	36 32	20 15	34 18
	Elek River basin	ΣP_{VI-XI}	161	SSP3-7.0 SSP5-8.5	14 9	7 10	12 5
	Ulken Kobda River basin	ΣP_{VI-XI}	152	SSP3-7.0 SSP5-8.5	−7 −11	−21 −13	−21 −19
Right-bank tributaries of the Zhaiyk River	Shagan River basin	ΣP_{VI-XI}	192	SSP3-7.0 SSP5-8.5	−2 −2	−4 −11	−10 −18
Southern rivers	Emba River basin	ΣP_{VI-XI}	116	SSP3-7.0 SSP5-8.5	14 11	3 22	10 7
	Oyl River basin	ΣP_{VI-XI}	117	SSP3-7.0 SSP5-8.5	14 14	0 17	−5 −15

At the same time, air temperature is projected to rise significantly, particularly under SSP5-8.5, with increases of 2.6 °C (SSP3-7.0) and 2.8 °C (SSP5-8.5) by 2040; 3.7 °C (SSP3-7.0) and 4.1 °C (SSP5-8.5) by 2060; and 4.8 °C (SSP3-7.0) and 5.3 °C (SSP5-8.5) by 2080.

For the Ulken Kobda River, a slight decrease in minimal runoff during the summer–autumn low-water period is expected for all forecast periods under both scenarios. By 2040, minimal runoff is projected to decrease by 1% under SSP3-7.0 and by 2% under SSP5-8.5.

By 2060, the reduction is expected to reach 10% under SSP3-7.0 and 7% under SSP5-8.5, and by 2080, the decrease will amount to 13% under SSP3-7.0 and 20% under SSP5-8.5.

Table 8. Projected changes in summer–autumn season air temperature in the territory of the Zhaiyk–Caspian water management basin.

Hydrological Area	River Basin	Predictor	Base Period (1991–2020)	Future Scenario	2040 (2031–2050)	2060 (2051–2070)	2080 (2071–2090)
			Actual Measured Value, °C		Projected Increase, °C	Projected Increase, °C	Projected Increase, °C
Left-bank tributaries of the Zhaiyk River	Or River basin	$T_{avg.VI-XI}$	12.3	SSP3-7.0 SSP5-8.5	2.6 2.7	3.6 4.0	4.7 5.7
	Elek River basin	$T_{avg.VI-XI}$	13.4	SSP3-7.0 SSP5-8.5	2.6 2.8	3.7 4.1	4.8 5.3
	Ulken Kobda River basin	$T_{avg.VI-XI}$	14.2	SSP3-7.0 SSP5-8.5	2.3 2.5	3.6 4.0	4.8 5.9
Right-bank tributaries of the Zhaiyk River	Shagan River basin	$T_{avg.VI-XI}$	14.1	SSP3-7.0 SSP5-8.5	2.3 2.6	3.6 4.1	4.7 5.5
Southern rivers	Emba River basin	$T_{avg.VI-XI}$	14.6	SSP3-7.0 SSP5-8.5	1.7 1.9	2.8 3.4	4.1 5.1
	Oiyl River basin	$T_{avg.VI-XI}$	15.3	SSP3-7.0 SSP5-8.5	2.5 2.7	3.8 4.2	5.0 6.1

For the Karakobda River, a progressive and more pronounced decline in runoff is forecasted. By 2040, minimal runoff is expected to decrease by 22% under SSP3-7.0 and by 26% under SSP5-8.5. The decline will intensify, reaching 40% (SSP3-7.0) and 42% (SSP5-8.5) by 2060, and 53% (SSP3-7.0) and 59% (SSP5-8.5) by 2080.

Precipitation dynamics in this area are projected to be synchronous with runoff. According to forecasts, precipitation will also decline progressively: under SSP3-7.0, a decrease of 7% is expected by 2040, increasing to 21% by both 2060 and 2080; under SSP5-8.5, precipitation is projected to decrease by 11% by 2040 and by 19% by 2080. By the end of the century, average summer–autumn air temperatures are projected to rise by 4.8 °C under SSP3-7.0 and by 5.9 °C under SSP5-8.5.

Unlike these rivers, minimal runoff during the summer–autumn low-water period in the Or River is projected to increase significantly under both scenarios. Under SSP3-7.0, minimal runoff is expected to increase by 42% by 2040, 43% by 2060, and 68% by 2080. Under SSP5-8.5, the increase is projected to reach 41% by 2040, 44% by 2060, and 68% by 2080.

Precipitation in the Or River basin is expected to increase synchronously with runoff. Under SSP3-7.0, precipitation is projected to rise by 36% by 2040, 20% by 2060, and 34% by 2080; under SSP5-8.5, precipitation is expected to increase by 32% by 2040, 15% by 2060, and 18% by 2080. By the end of the century, summer–autumn season temperatures are projected to rise by 4.7 °C under SSP3-7.0 and to 5.7 °C under SSP5-8.5, based on observations at the Novorossiyskoye meteorological station.

In the right-bank area of the Zhaiyk River, projected trends of decreasing precipitation combined with a significant increase in air temperature will lead to a stable decline in the minimal summer–autumn low-water runoff of the Shagan River. According to the SSP3-7.0 scenario, minimal runoff is expected to decrease by 26% by 2040, 49% by 2060, and 63% by 2080. Under the SSP5-8.5 scenario, the corresponding reductions are projected at 31%, 53%, and 71%, respectively. Precipitation is forecasted to decrease by 2%, 4%, and 10% under SSP3-7.0 by 2040, 2060, and 2080, respectively, and by 2%, 11%, and 18% under SSP5-8.5 for the same periods. Temperature is expected to increase by 2.3 °C, 3.6 °C, and 4.7 °C under SSP3-7.0, and by 2.6 °C, 4.1 °C, and 5.5 °C under SSP5-8.5 across the three forecast periods.

The southern rivers of the basin demonstrate the most pronounced and systematic reductions in minimal runoff under both climate scenarios. By 2040, the reduction in minimal runoff is projected to range from 7% for the Temir River under SSP3-7.0 to 22% for the Oiyl River under SSP5-8.5. By 2060, the reduction intensifies to 32–33% for all rivers under SSP3-7.0, and to 35% for the Zhem and Oiyl rivers under SSP5-8.5. By 2080, significant decreases in minimal runoff are forecasted, with reductions ranging from 45% (Temir and Oiyl rivers) to 49% (Zhem River) under SSP3-7.0, and from 56% (Oiyl River) to 65% (Zhem River) under SSP5-8.5.

The divergent trends in forecasted precipitation for the southern river basins suggest that summer–autumn precipitation exerts a relatively minor influence on minimal runoff, while air temperature plays a dominant role. According to projections, summer–autumn temperatures in the region will gradually increase. By the end of the century, the maximum projected temperature increase reaches 4.1 °C for the Zhem River basin under SSP3-7.0 and 5.1 °C under SSP5-8.5. For the Oiyl River basin, temperature increases are projected at 5.0 °C (SSP3-7.0) and 6.1 °C (SSP5-8.5).

3.3. Projection of Minimal Runoff During the Winter Low-Water Period

Forecast results presented in Figure 8 indicate that under both climate scenarios, a steady increase in minimal monthly runoff during the winter low-water period is expected across all considered rivers for the forecast horizons of 2040, 2060, and 2080. The results are graphically presented in Figure 9. Seasonal changes in precipitation and air temperature for the Zhaiyk–Caspian water management basin under future climate conditions are provided in Tables 9 and 10.

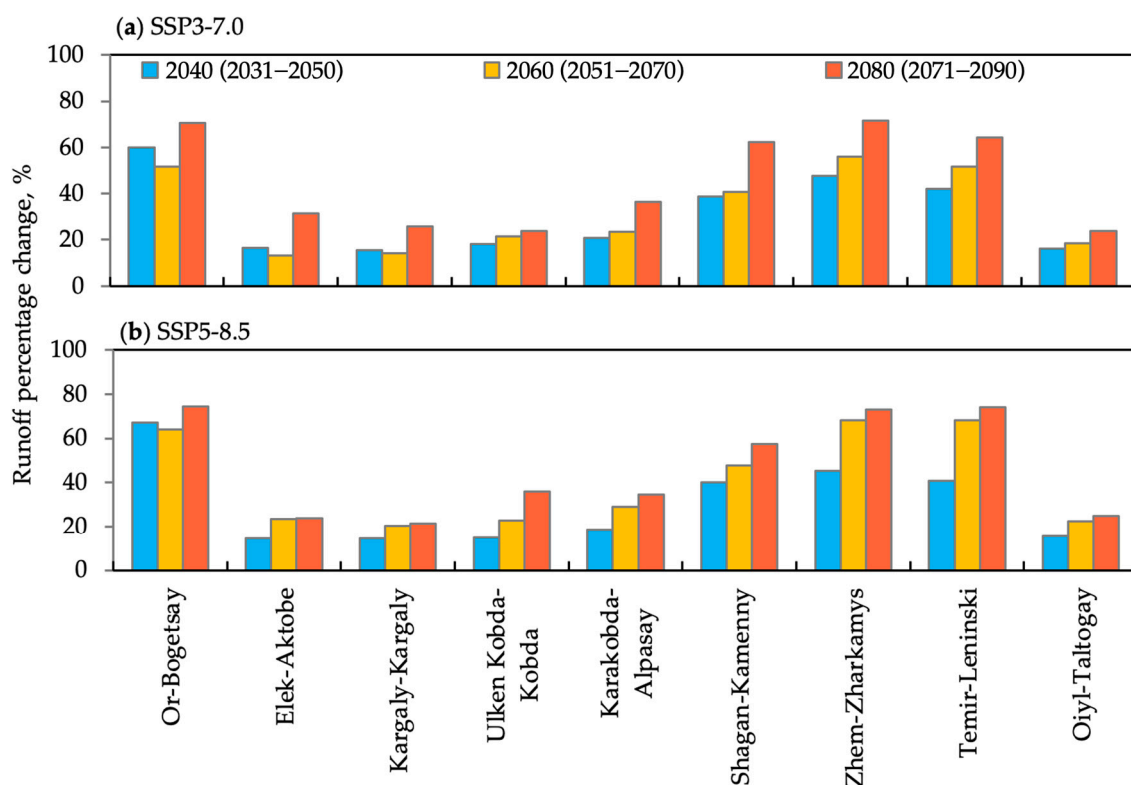


Figure 9. Projected percentage changes in the average monthly minimal runoff of the winter low-water period of rivers in the Zhaiyk–Caspian water management basin relative to the historical average (1991–2020).

Table 9. Projected changes in precipitation amounts during the winter season in the Zhaiyk–Caspian water management basin territory.

Hydrological Area	River Basin	Predictor	Base Period (1991–2020)	Future Scenario	2040 (2031–2050)	2060 (2051–2070)	2080 (2071–2090)
			Actual Measured Value, mm		Rate of Change, %	Rate of Change, %	Rate of Change, %
Left-bank tributaries of the Zhaiyk River	Or River basin	ΣP_{IX-II}	166	SSP3-7.0	43	36	61
				SSP5-8.5	42	48	46
	Elek River basin	ΣP_{IX-II}	160	SSP3-7.0	47	37	64
				SSP5-8.5	44	51	45
	Ulken Kobda River basin	ΣP_{XII-II}	86	SSP3-7.0	13	11	49
		ΣP_{X-II}	85	SSP5-8.5	20	35	33
Right-bank tributaries of the Zhaiyk River	Shagan River basin	ΣP_{X-II}	144	SSP3-7.0	47	41	74
				SSP5-8.5	42	55	47
Southern rivers	Emba and Oiyl river basins	ΣP_{XII-II}	61	SSP3-7.0	26	23	42
				SSP5-8.5	27	31	28

Table 10. Projected changes in air temperature during the winter season in the Zhaiyk–Caspian water management basin territory.

Hydrological Area	River Basin	Predictor	Base Period (1991–2020)	Future Scenario	2040 (2031–2050)	2060 (2051–2070)	2080 (2071–2090)
			Actual Measured Value, °C		Projected Increase, °C	Projected Increase, °C	Projected Increase, °C
Left-bank tributaries of the Zhaiyk River	Or River basin	$T_{avg,I-III}$	−12.7	SSP3-7.0	3.5	4.9	6.0
				SSP5-8.5	3.7	5.6	6.9
	Elek River basin	$T_{avg,I-II}$	−12.0	SSP3-7.0	1.7	2.9	4.3
				SSP5-8.5	1.9	3.7	5.6
	Ulken Kobda River basin	$T_{avg,I-II}$	−11.6	SSP3-7.0	2.2	3.6	5.0
				SSP5-8.5	2.5	4.2	6.1
Right-bank tributaries of the Zhaiyk River	Shagan River basin	$T_{avg,XII-II}$	−9.7	SSP3-7.0	2.0	3.3	4.3
				SSP5-8.5	2.3	3.9	6.0
Southern rivers	Emba River basin	$T_{avg,XII-II}$	−11.1	SSP3-7.0	2.1	3.4	4.7
				SSP5-8.5	2.4	4.0	5.7
	Oiyl River basin	$T_{avg,I-II}$	−11.1	SSP3-7.0	3.8	4.9	6.1
				SSP5-8.5	4.0	5.5	7.2

Among the left-bank tributaries of the Zhaiyk River, the Or River shows the most pronounced changes, with minimal runoff projected to increase by 60% (SSP3-7.0) and 67% (SSP5-8.5) by 2040; by 52% and 64%, respectively, by 2060; and by 70% (SSP3-7.0) and 74% (SSP5-8.5) by 2080.

The Elek River and its tributary, the Kargaly River, are also projected to exhibit positive dynamics. By 2040, minimal runoff is expected to increase by 16–17% under SSP3-7.0 and by 14% under SSP5-8.5. By 2060, the increase is projected to range from 13–14% (SSP3-7.0) to 20–23% (SSP5-8.5). By 2080, minimal runoff is expected to continue increasing, reaching 26–31% under SSP3-7.0 and 21–24% under SSP5-8.5.

For the Ulken Kobda and Karakobda rivers, a stable and gradual increase in minimal runoff is projected throughout the forecast period. By 2040, runoff is expected to increase by 18–21% under SSP3-7.0 and by 15–19% under SSP5-8.5. By 2060, increases are projected to reach 22–24% (SSP3-7.0) and 23–29% (SSP5-8.5). By 2080, minimal runoff is projected to increase by 24–36% under SSP3-7.0 and by 35–36% under SSP5-8.5.

The territory of the left-bank tributaries of the Zhaiyk River is characterized by synchronous dynamics between river flow and precipitation during the autumn season and the cold period, as evidenced by both historical observations and future projections. Winter precipitation in this area is expected to increase under the SSP3-7.0 scenario from 13% by 2040 to 49% by 2080, and under the SSP5-8.5 scenario from 20% by 2040 to 35% by 2060. The total precipitation for the autumn and winter seasons under SSP3-7.0 is projected to increase, on average, by 43–47% by 2040, 36–41% by 2060, and 61–74% by 2080. Under SSP5-8.5, precipitation is expected to increase by 42–47% by 2040, 48–55% by 2060, and 45–47% by 2080.

Forecast data also indicate a steady increase in average air temperatures for January and February across the area, continuing through the end of the century. The projected increase in average air temperature is 2.0 °C, 3.2 °C, and 4.6 °C under the SSP3-7.0 scenario, and 2.2 °C, 3.9 °C, and 5.8 °C under the SSP5-8.5 scenario for the forecast periods.

A pronounced increase in river flow, synchronous with future precipitation trends, is forecasted for the Shagan River. According to the SSP3-7.0 scenario, minimal runoff is expected to increase by 39% by 2040, 41% by 2060, and 62% by 2080. Under the SSP5-8.5 scenario, the projected increases are 40%, 48%, and 57%, respectively. During the first two forecast periods, precipitation in the region is projected to increase by up to 31% by 2060 under the SSP5-8.5 scenario. By the end of the century, precipitation is expected to increase by up to 42% under SSP3-7.0 and 28% under SSP5-8.5.

In addition, air temperature in the area of the right-bank tributaries of the Zhaiyk River is projected to increase by 4.3 °C under SSP3-7.0 and by 6.0 °C under SSP5-8.5 by the end of the century.

Among the southern rivers, significant increases in minimal winter runoff are projected for the Zhem River and its tributary, the Temir River. According to the SSP3-7.0 scenario, minimal runoff is expected to increase by 42–48% by 2040, 56–62% by 2060, and 64–71% by 2080. Under the SSP5-8.5 scenario, the projected increases are 41–45% by 2040, 68% by 2060, and 73–74% by 2080.

Scenario-based forecasts for the Oiyl River also indicate positive changes, though to a lesser extent. By 2040, minimal runoff is expected to increase by 16% under both scenarios, by 18–22% by 2060 (SSP3-7.0 and SSP5-8.5, respectively), and by 24–25% by 2080 under both scenarios.

Precipitation in this area is projected to increase under the SSP3-7.0 scenario by 48% in 2040 and 2060, reaching 71% by 2080. Under the SSP5-8.5 scenario, precipitation is expected to increase by 49% in 2040, 71% in 2060, and 57% in 2080.

The average air temperature for the December–February period by the end of the 21st century is projected to increase by 4.7 °C under SSP3-7.0 and by 5.7 °C under SSP5-8.5, relative to the baseline period. For the January–February period specifically, temperatures are projected to rise by 6.1 °C under SSP3-7.0 and by 7.2 °C under SSP5-8.5 by 2080.

The quality of the methodology was evaluated according to the criteria proposed by [17], taking into account the correlation coefficient (r) between observed and predicted values.

For verification periods longer than 25 years, the methodology demonstrated a satisfactory forecast performance for both the summer–autumn and winter minimal runoff, as interpreted in Table 11.

Table 11. Evaluation of the forecast quality for minimal runoff.

Low-Flow Period	S/σ	ρ	Methodological Quality Rating
Summer-Autumn	0.69–0.81	0.60–0.75	Satisfactory
Winter	0.77–0.80	0.61–0.67	Satisfactory

The accuracy indicators fall within the established standards, confirming the applicability of the selected approach for climate-sensitive assessment of minimal runoff.

4. Discussion

Long-term hydrological monitoring in various catchments of Kazakhstan plains reveals both intra-annual runoff redistribution and emerging trends in total annual runoff, highlighting the need for new approaches to characterizing low-flow conditions and supporting water resource management decisions [18,20]. Among the available methods, scenario-based hydrological projections that incorporate observed and projected climatic and hydrological changes are increasingly applied in research and practice. This trend has been facilitated by recent advances in global and regional climate modelling [21–23].

Within the framework of the World Climate Research Programme (WCRP), CMIP6 provides a new generation of climate scenarios, known as Shared Socioeconomic Pathways (SSPs). These scenarios combine trajectories of socioeconomic development with pathways of anthropogenic changes in atmospheric greenhouse gas concentrations, expanding upon the Representative Concentration Pathways (RCPs) framework introduced in the previous CMIP5 project. The RCPs—specifically RCP2.6, RCP4.5, RCP6.0, and RCP8.5—formed the basis for earlier climate change projections and are incorporated within the broader SSP framework of CMIP6 [24]. CMIP6 simulations offer a valuable basis for assessing regional climate change impacts, including those affecting water resources, by providing a wide range of plausible future climate conditions consistent with both socioeconomic and emission-related factors.

Most previous research has focused on scenario-based projections of annual river runoff. For instance, the authors of [25] highlighted considerable uncertainty in projections of annual runoff changes derived from an ensemble of nine global climate models participating in the CMIP3 project. In that study, substantial calculation errors and a wide inter-model spread were reported for the Volga River basin, with projected anomalies in total annual runoff ranging from -14% to $+27\%$. In a more recent study by [26], multi-year average differences between precipitation and evaporation, calculated from 26 CMIP5 models, were used to characterize annual runoff across Russia. Positive anomalies were identified for almost all rivers, except those located in southern Russia. The largest positive anomalies by the end of the 21st century were projected under the unfavourable RCP8.5 scenario, reaching 34% for the Lena River, 27% for the Yenisei River, and 42% for the total runoff of rivers in northeastern Siberia.

The application of CMIP6 climate models is essential for assessing future water resources for several reasons. First, they provide a broad range of plausible future climate projections that can be applied to scenario-based assessments across different regions and time horizons. Second, CMIP6 includes key climate variables, such as air temperature and atmospheric precipitation, that directly affect the availability and distribution of water resources. Third, these scenario-based forecasts represent important tools for developing water resource management strategies, including water supply planning, irrigation management, and flood and hydrological drought risk assessment. Finally, improving knowledge of future climate conditions enables the implementation of adaptation measures to enhance the resilience of water systems under changing climatic conditions.

From a scientific and methodological perspective, CMIP6 offers notable advantages over the previous generation of models (CMIP5), providing improved accuracy and enhanced information for hydrological research, including scenario-based forecasting of low-water runoff. However, previous studies have demonstrated that assessments of water regime characteristics for individual river basins based on climate models often carry significant uncertainties, primarily due to inaccuracies in estimating atmospheric precipitation at

the regional scale and substantial simplifications in the representation of hydrological processes [27,28]. Nevertheless, recent advancements in CMIP6 models, including increased computational efficiency and improved parameterizations of land surface hydrological processes, have partially mitigated these limitations [29].

The results of the present study confirm consistent changes in air temperature and atmospheric precipitation patterns within the Zhaiyk–Caspian water management basin, which have a direct influence on the formation of minimum low-water runoff. The primary factors affecting the quantitative characteristics of minimum river discharge during the summer–autumn low-water period are atmospheric precipitation and air temperature during the same season. Scenario-based projections derived from CMIP6 models indicate an expected increase in summer–autumn precipitation across much of the basin. Nevertheless, a consistent reduction in minimum runoff is projected for most rivers, particularly in the southern part of the basin, across all future periods and under both greenhouse gas scenarios. These results are consistent with established climatic trends for the northern mid-latitudes [30]. The apparent contradiction between increasing precipitation and decreasing minimum flow can be explained by the compensating effects of increased evapotranspiration and reduced soil moisture reserves due to rising air temperatures, ultimately contributing to reductions in both surface and groundwater contributions to river flow [31].

Conversely, during the winter low-water period, an increase in minimum river discharge is projected for all watercourses in the study region of Western Kazakhstan. This is likely associated with enhanced infiltration recharge resulting from more frequent winter thaws and increased winter precipitation. While autumn precipitation is traditionally considered the main source of groundwater recharge during the winter period, it alone cannot explain the observed and projected increases in minimum winter runoff, given the statistically insignificant trends in autumn precipitation observed at most meteorological stations in the basin.

Long-term dynamics of winter precipitation, in contrast, exhibit significant positive trends across most of the basin, albeit with substantial spatial variability. Similar conclusions were reached by other researchers [6], who demonstrated that autumn precipitation alone is insufficient to sustain winter runoff recharge in the Volga River basin. Therefore, when assessing the formation of minimum winter runoff under ongoing climate change, it is advisable to consider the combined influence of both autumn and winter precipitation.

Changes in groundwater levels must also be considered a contributing factor. Under significant winter warming, snowmelt generated by more frequent thaws, combined with increased winter precipitation, can provide an additional source of river recharge and contribute to higher groundwater levels. A substantial portion of the water generated during thaws is retained in the active soil layer, enhancing soil moisture and promoting infiltration recharge and groundwater replenishment. These processes are consistent with the findings of several other studies [6,32,33]. Furthermore, recent observations confirm a rise in the frequency and duration of winter thaws in the region [34]. Scenario-based projections for the basin indicate a stable increase in minimum river discharge during the winter low-water period across all forecast horizons and under both climate scenarios. These results demonstrate that rising winter temperatures are accompanied by increased precipitation, consistent with the findings of [35]. Together, these changes contribute to greater snowmelt volumes, ultimately leading to higher base flow during the winter period.

It is important to emphasize that the projections of minimum river discharge presented in this study are subject to inherent uncertainties associated with the use of global and regional climate models, as well as the applied methodological approach. The range of projected changes in minimum runoff across different rivers and time periods, as illustrated in the tables and figures, reflects both the variability among the selected CMIP6 models and

the influence of different greenhouse gas concentration scenarios. Although the ensemble of models employed in this study provides a representative spectrum of possible future climate conditions, significant uncertainty persists regarding both the magnitude and spatial distribution of projected changes, particularly for the summer–autumn low-water period, where the combined effects of precipitation and temperature changes on runoff formation are complex and nonlinear.

In addition to model-related uncertainty, it is essential to recognize methodological limitations. The statistical relationships established between minimum runoff and meteorological predictors are based on historical observations and assume their stability under future climate conditions. However, potential non-stationarity in hydrological processes, changes in land use, and groundwater dynamics—factors not explicitly accounted for in the applied models—may alter these relationships, especially under extreme climate scenarios.

Despite these limitations, the consistent spatial and seasonal patterns identified in the projections, together with the physical plausibility of the underlying processes, increase confidence in the qualitative trends described. Nevertheless, future research should incorporate more comprehensive uncertainty assessments, including probabilistic approaches, multi-model ensembles, and improved representation of groundwater processes, to further enhance the robustness of runoff projections and support the development of climate-resilient water management strategies in Western Kazakhstan.

5. Conclusions

This study provides a scenario-based assessment of future changes in minimum river discharge in the Zhaiyk–Caspian water management basin of Western Kazakhstan under projected climate change conditions. Using an ensemble of dynamically downscaled CMIP6 climate models for Central Asia, low-flow conditions were estimated for the summer–autumn and winter low-water periods for three future time horizons (2040, 2060, and 2080) under two greenhouse gas concentration scenarios (SSP3-7.0 and SSP5-8.5).

The results reveal a pronounced seasonal contrast in the projected hydrological response to climate change. During the summer–autumn low-water period, a widespread reduction in minimum river discharge is expected, particularly for rivers in the southern part of the basin, including the Zhem, Oiyl, and Temir rivers. This projected decline, which may reach up to 64% by the end of the century, is primarily attributed to increased evapotranspiration and soil moisture deficits driven by rising air temperatures, which offset the potential positive effects of increased precipitation.

In contrast, during the winter low-water period, a steady increase in minimum discharge is projected for all analysed rivers, with the Or, Zhem, Temir, and Shagan rivers showing the most substantial changes. This increase is associated with higher winter precipitation and air temperatures, which collectively enhance the frequency of thaws, promote infiltration processes, and contribute to groundwater recharge, ultimately leading to higher winter baseflow.

The analysis also indicates that changes in winter discharge cannot be explained by autumn precipitation alone, emphasizing the need to account for the combined effects of seasonal precipitation patterns, snowmelt dynamics, and groundwater contributions when assessing future low-water conditions.

It should be acknowledged that these projections are subject to uncertainties arising from the limitations of climate models, regional downscaling techniques, and the simplified representation of hydrological processes. Nevertheless, the consistency of the spatial and seasonal patterns identified, supported by physically plausible mechanisms, provides a reliable basis for informing water resource management and climate adaptation planning in the region.

These findings underscore the importance of developing seasonally differentiated, climate-resilient water management strategies. Priority should be given to mitigating summer–autumn low-flow risks in the southern basins while also considering opportunities to manage increased winter runoff.

Further research is needed to improve the representation of groundwater processes in hydrological models, to integrate socioeconomic factors such as land use and water management changes, and to apply high-resolution regional modelling to reduce uncertainties in low-flow projections. In particular, detailed field investigations on groundwater–surface water interactions and the role of snowpack dynamics are essential for refining future assessments of minimum river discharge under evolving climate conditions.

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