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Impact of Climatic Conditions on Extremely Low Water Discharges in the Steppe Basins of Kazakhstan

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ABSTRACT

This study investigates the spatiotemporal variability of minimum river discharge in Northern Kazakhstan and its sensitivity to climatic factors under continental and semi-arid conditions. Long-term meteorological and hydrological data from key regional rivers, including Tobyl, Toguzak, Torgay, Karatorgay, and Ayat, were analyzed to detect structural shifts, trends, and stationarity. Structural changes were identified using Pettitt's test and supported by difference-integral and cumulative-integral curves, while linear trend analysis with 10-year moving averages highlighted long-term tendencies. Correlation analysis assessed the influence of temperature and precipitation, distinguishing low- and high-flow years. Stationarity and homogeneity were evaluated with ADF, KPSS, and complementary parametric and non-parametric tests to ensure robust statistical interpretation. Results reveal significant structural shifts during 1980–1990, with rising winter air temperatures and marked heterogeneity of minimum discharge, especially in cold seasons. Winter flows are predominantly controlled by temperature and groundwater recharge, while summer flows are strongly linked to precipitation dynamics and evapotranspiration processes. Differences between low- and high-flow years confirm the dynamic non-stationarity of the system. These findings enhance understanding of regional hydro-climatic interactions and provide a scientific basis for adaptive water resource management, reservoir regulation, and long-term strategies of climate change adaptation in the steppe and semi-arid regions of Central Asia.

Keywords:, *Low-flow discharge, Climatic factors, Stationarity, Northern Kazakhstan, Climate adaptation*

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INTRODUCTION

Within a framework for global climate change, there is an observed increase in air temperatures combined with shifts in precipitation patterns, which together impact hydrological cycles across different spatial and temporal scales (Trenberth *et al.*, 2014; IPCC, 2021). River catchments in arid and semi-arid regions are particularly sensitive to climate variations, making low flow a key indicator of both water supply sustainability and ecological health in catchments within a river basin (Kundzewicz *et al*., 2008; Shiklomanov & Lammers, 2020; Birimbayeva *et al*., 2024; Makhmudova *et al*., 2024; Abdykadyrov *et al*., 2025).

Analysis of low-flow discharge allows for a determination of long-term trends in either deterioration or recovery of the water regime, as well as for an estimation of climatic sensitivity of hydrological catchments. In north Kazakhstan and in adjacent Soviet Urals regions marked by a prevalence of steppe landscapes with a sharply continental climate, minimum discharge values, primarily those for summer and winter periods with low flow, are dependent upon an interaction between thermobaric regimes, freezing and moisture-accumulation regimes, and infiltration- and groundwater contributions (Dyachenko & Maznev, 2017; Belyaev *et al*., 2019; Makhmudova *et al*., 2024; Smagulov *et al*., 2025).

Despite a substantial amount of empirical data, the spatial variation in how climate impacts low flow remains poorly understood. This lack of knowledge applies both to differences between winter and summer regimes and to how much these relationships are influenced by year-to-year changes in water availability. A major research effort should focus on examining structural breaks in climatic and hydrological time series and on understanding the relative roles of precipitation and temperature in driving extremely low water discharge values (Zhang *et al*., 2020; Ivanov & Shlykov, 2022).

This study aims to provide a comprehensive assessment of climatic factors, namely precipitation and air temperature, and their effect on low-flow discharge at hydrological measurement stations in northern Kazakhstan. The analysis includes consideration of seasonal features, between-year variations in wet and dry periods, alongside structural shifts and longer-term trends.

Research includes a comprehensive overview of the geographical location of measurement stations and climate zones, sources and duration of observations, along with employed analytical procedures, including statistical analysis, trend analysis, and correlation analysis. Special focus is given to breakpoint selection criteria in addition to year classification for water availability.

MATERIALS AND METHODS

The research scope comprises hydrological gauging stations located in small to medium catchments in north Kazakhstan, specifically the Toguzak River, the Tobyl River (in proximity to Grishenka village and Kostanay city), the Ayat River (reach near Varvarinka village), the Karatorgay River, and the Torgay River. These gauging stations encompass lowland as well as foot-slope catchments within the belted basin of Esil and some parts of the basin of Tobyl **(Figure 1)**. Low flow discharge was estimated independently for winter and summer low flow periods, thereby allowing consideration of variations in feeding mechanisms like groundwater, infiltration, and precipitation.

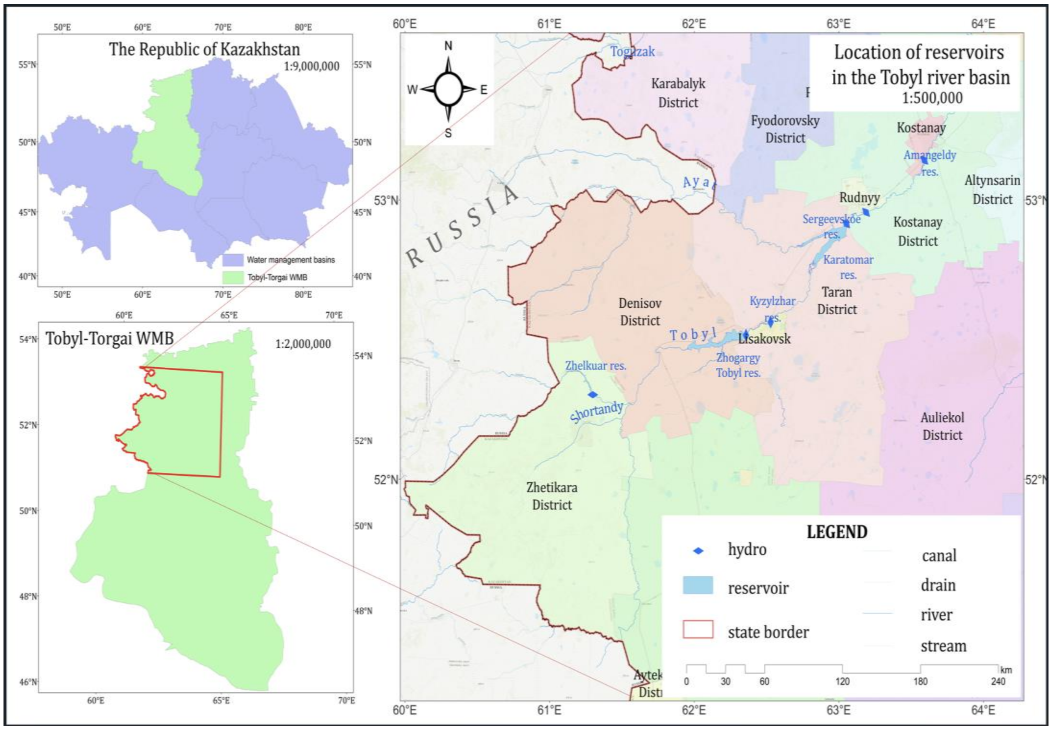


Figure 1. Tobyl–Torgay water management basin (Nugmanov *et al*., 2025)

Data for discharge cover the period from the 1930s up to 2020 and were taken from RSE "Kazhydromet" archival collections and processing reports. Also, auxiliary information about air temperature and precipitation was taken from the Kostanay meteorological station, providing a fine approximation for the climatic conditions of the study area. The observation period includes 1935–2021.

The analysis employed a range of statistical and graphical forms of analysis commonly used in hydrology and climatology. To identify structural breakpoints in the time series for temperature, precipitation, and low-flow discharge, use was made of the Pettitt test (Pettitt, 1979), so as to make it possible for a shift in a dataset's median structure with an indeterminate transition duration to be identified at a specific point. Analysis of trend was performed using linear regression, calculation of the slope for the time series, and assessment of significance using the Student's t-test, following procedures outlined in previous literature (Kundzewicz & Robson, 2000). Tests for stationarity were performed using the Augmented Dickey-Fuller (ADF) test and the KPSS test, which allow for an estimation of the presence or absence of a unit root or a component of trend (Said & Dickey, 1984, Kwiatkowski *et al*., 1992). To test the correlation between climatic variables and discharge at low flow, the Pearson pairwise correlation coefficient was used. Multivariate analysis was conducted on the full set of data as a whole and separately for wet years (Qmax ≥ 0.25 percentile) and dry years (Qmin ≤ 0.75 percentile). Such an approach allowed for an estimation of modified climatic impacts on river discharge for varying hydrological conditions.

Further, the residual mass curve as well as the cumulative sums technique was employed, a standard technique for representing extended variations within hydrological settings (Burn & Hag Elnur, 2002; Maznev, 2009).

RESULTS AND DISCUSSION

Breakpoints and trends in climatic parameters

The analysis of long-term series of air temperature and precipitation from the Kostanay meteorological station for the period 1935–2021 revealed the presence of structural breakpoints and persistent positive trends, particularly pronounced in temperature variables. Application of the non-parametric Pettitt test (Pettitt, 1979), designed to detect unknown points of structural change in time series, indicated statistically significant breakpoints at the following moments:

1. Mean annual air temperature – breakpoint in 1980 ($p < 0.01$);
2. Cold season temperature (October–March) – breakpoint in 1980 ($p < 0.01$);
3. Warm season temperature (April–September) – breakpoint in 1973 ($p < 0.01$).

In all cases, the detected trends are positive and statistically significant ($p < 0.01$), with the highest rate of increase observed for cold-season temperature (+0.0491 °C per year, $R^2 = 0.61$). The analysis of long-term climatic variables—air temperature and precipitation—thus demonstrates persistent trend shifts and structural non-stationarity, particularly evident in temperature characteristics.

It should be noted that in all of the above cases, temperature series display stable positive dynamics, confirmed by linear trend analysis. The most pronounced increase was recorded during the cold season, where the rate of warming reached +0.0491 °C per year, with a coefficient of determination (R^2) of 0.61, indicating a high level of explained variance and robustness of the trend.

By contrast, the analysis of precipitation revealed substantially lower variability. Weakly positive trends were observed, but they were not always statistically significant. Precipitation exhibited lower variability and a weakly positive trend, with significant breakpoints detected only for the cold season; the structural shift in precipitation sums was identified at the boundary of significance ($p = 0.063$).

Thus, it can be concluded that temperature regimes exhibit a more pronounced and persistent dynamic than precipitation regimes, which is consistent with global and regional climatic trends documented in comparable studies (Kundzewicz *et al*., 2008, IPCC, 2021).

Hydrological restructuring and changes in low-flow discharge

The low-flow regime of the rivers analyzed in this investigation exhibits distinct indications of structural alterations in hydrological dynamics, evident in both the statistical framework of time series and the trajectory and magnitude of long-term trends. The analysis indicated that all monitoring stations within the region underwent structural shifts during the interval from 1976 to 1992, as determined through the application of the Pettitt test (Pettitt, 1979) **(Table 1).** In various instances, these shifts were associated with modifications in trend slope—from stable or positive values to negative ones—most notably observed for the Toguzak River and the Tobyl River (Grishenka station) during the winter low-flow season.

Table 1. Structural shifts of minimum flow in rivers of the Tobyl–Torgay water management basin

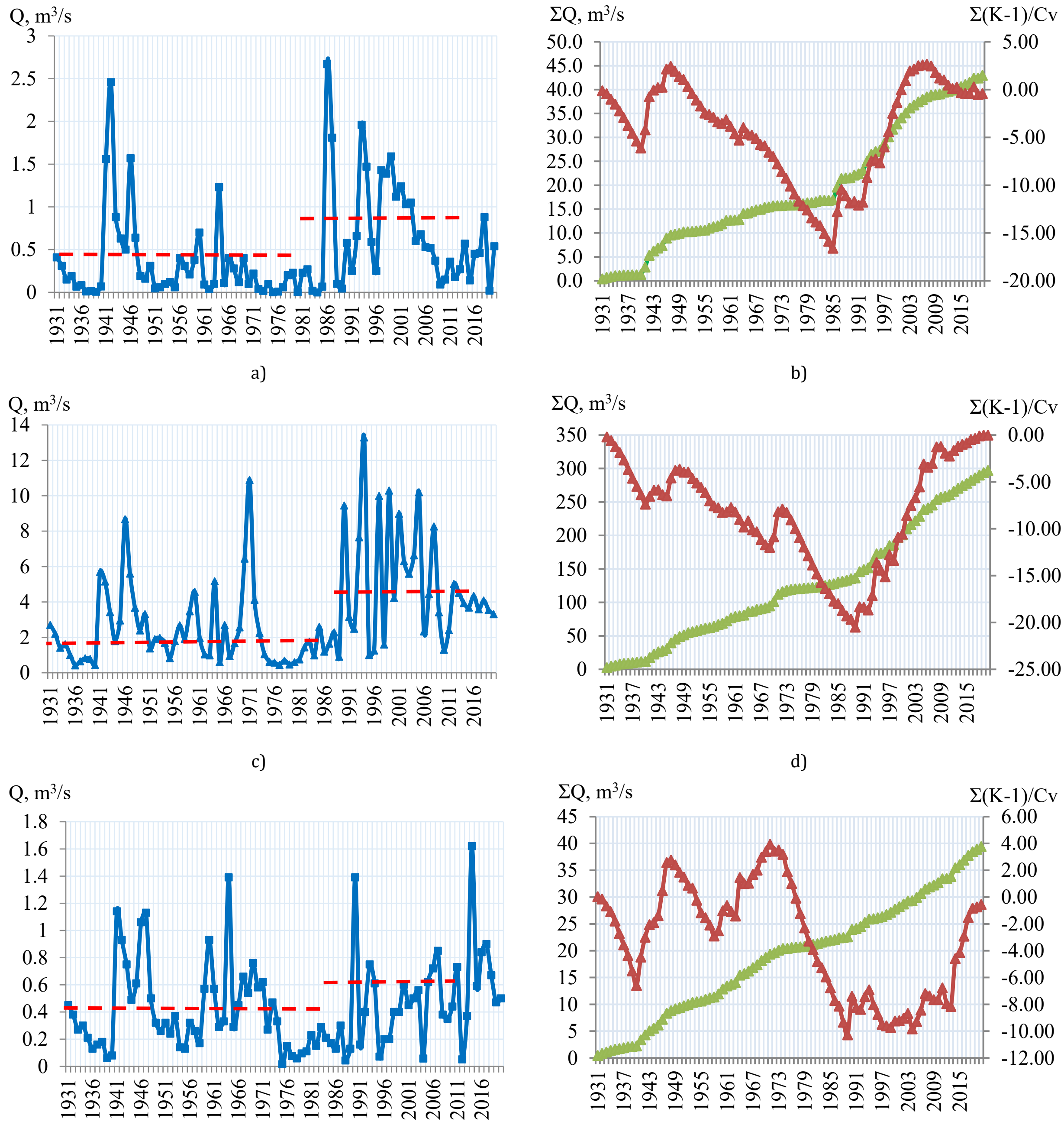
No.	Observation Point	Year of Structural Shift	Pettitt Statistic	p-value	Note
			Summer period		
1	Toguzak – s. Togyzak	1989	615.0	0.09203	–
2	Tobyl – s. Grishenka	1985	1044.0	0.00028	Climate humidification, flow stabilization
3	Tobyl – g. Kostanay	1989	1129.0	0.00006	Increase in minimum flow after regulation (Karatomar Reservoir)
4	Kara-Torgay – s. Urpek	1981	1077.0	0.000005	Sharp zeroing of flow after the 1990s
			Winter period		
1	Toguzak – s. Togyzak	1992	1364.0	0.00000006	Transition from zero values to stable flow after 1992
2	Tobyl – s. Grishenka	1976	1021.0	0.000085	No flow before 1976, followed by a stable increase
3	Tobyl – g. Kostanay	1988	1335.0	0.000001	Sharp rise in winter flow after 1988
4	Kara-Torgay – s. Urpek	–	–	–	The river freezes to the bottom in winter, with the flow absent.

The structural breakpoints identified by the Pettitt test were further confirmed by residual mass and cumulative sum curves **(Figure 2)**.

The patterns that were observed underscore the seasonal specificity of river regime responses to alterations in climatic variables. In the winter low-flow period, the minimum discharges exhibit the greatest sensitivity to cold-season temperatures, indicating the impact of soil freezing depth, snow cover conditions, and infiltration feeding. Additionally, a consistent positive correlation was identified with mean annual air temperature, which serves as an indicator of an integrated thermal effect.

For low flows in summer, autumn-winter precipitation is typically the dominant driver. However, where evaporation loss is strong in arid climatic regimes, there may be a reverse relationship with temperature: high summer temperature leads not to an increase but a decrease in discharge due to greater evaporative loss in addition to a decrease in recharge to moisture in soils.

Therefore, the results confirm the occurrence of several climate-hydrological processes in controlling low-flow discharge in both winter and summer seasons. Such delineations are thus essential for developing adaptive measures for water resource management in a situation involving an increase in climate variability.



a)

b)

c)

d)

e)

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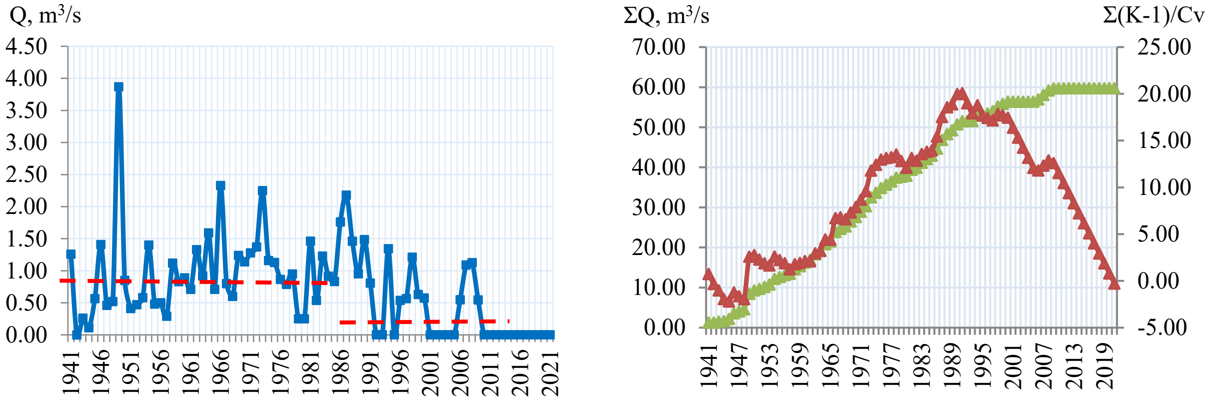


g) h)

Figure 2. Determination of the breakpoint in stationarity for the case of increase, stability, and decrease of minimum summer discharges (a, b – Tobyl River, Grishenka station; c, d – Tobyl River, Kostanay station; e, f – Toguzak River, Toguzak station; g, h – Karatorgay River, Urpek station). Left: breakpoint identified using the Pettitt test; right: by cumulative ΣQ and residual mass Σ(Ki-1)/Cv curves.

Impact of temperature and precipitation on low-flow discharge

A comparison of long-term low-flow series with climatic parameters (temperature and precipitation) revealed a strong dependence of discharge on climate factors, with pronounced seasonal and spatial variability **(Table 2)**.

Table 2. Correlation analysis between climatic parameters and minimum river flow

№	Observation point	Correlation coefficient between temperature and minimum flow			Correlation coefficient between precipitation and minimum flow		
		Year	Cold period	Warm period	Year	Cold period	Warm period
1	Toguzak – s. Togyzak	0,37/-0,1	0,41/0,06	0,16/0,32	0,33/0,43	0,27/0,1	0,21/0,43
2	Tobyl – s.Grishenka	0,28/0,68	0,31/0,60	0,13/0,55	0,34/0,28	0,27/0,34	0,23/0,12
3	Tobyl – Kostanay	0,31/0,68	0,31/0,60	0,19/0,57	0,11/0,27	0,20/0,34	0,014/0,10
4	Ayat – s. Varvarinka	-/0,10	-/0,23	-/-0,18	-/0,34	-/0,12	//0,31
5	Kara-Torgay – s. Urpek	-/0,27	-/-0,22	-/-0,25	-/-0,16	-/-0,24	-/-0,04
6	Torgay – Peski Tusum	-/-0,28	-/-0,16	-/-0,28	-/-0,04	-/-0,17	-/0,06

Correlation analysis showed that, on average across all gauging stations in the region, air temperature exerts a more consistent and pronounced influence on low-flow discharge than precipitation. This is most evident in the winter period, where correlation coefficients between air temperature and discharge reach *R* = 0.40–0.68, indicating a moderate and statistically significant relationship. Particularly important is the influence of cold-season temperature, reflecting soil freezing conditions, infiltration feeding, and the persistence of groundwater storage (Nasiyev *et al*., 2015; Shayakhmetova *et al*., 2023).

However, a number of gauging stations exhibited local deviations from the general pattern, which in turn highlights the complexity of interactions between climatic and hydrological factors. For example, at the Tobyl River – Kostanay station, a positive correlation was found between warm-season temperature and minimum summer discharge. This can be explained by the specific features of runoff formation at this site: earlier snowmelt, infiltration recharge, and a significant contribution of groundwater inflow, driven by the geomorphological and hydro-engineering characteristics of the catchment.

Therefore, summer discharge is primarily determined by precipitation and its interaction with evaporation and infiltration processes, whereas winter discharge is mostly influenced by the temperature regime. The identified heterogeneity of climatic sensitivity therefore requires a spatially differentiated approach to the analysis of river regimes under changing climate conditions.

Correlation analysis also showed that in the basins of the Karatorgay and Torgay rivers, a negative relationship is observed between total precipitation and minimum river discharge, both in summer and in winter. For the Karatorgay River during the summer season, correlation coefficients between precipitation (annual, cold season, and warm season) and minimum discharge ranged from *R* = −0.16 to −0.24, indicating a weak but persistent negative relationship. For the Torgay River, the relationship is weaker, approaching zero (*R* ≈ −0.036), which likewise points to the absence of a direct dependence between precipitation volume and the formation of minimum discharge.

During the winter period, river flow in these catchments often ceases completely due to deep channel freezing. Nevertheless, even under conditions of strongly limited water movement, a negative correlation was recorded between winter precipitation and discharge, which requires further detailed investigation (Ahn *et al*., 2025; Castellano-Rioja, 2025; Cavero & Ferraz, 2025; Hart & Reed, 2025; Khalil & Nassar, 2025; Rani & Gehrke, 2025; Rivas & Molina, 2025; Rojas & Paredes, 2025; Shen & Bao, 2025; Silik, 2025).

The basins of the Kara-Torgai and Torgay rivers are located in an arid climate zone, characterized by low annual precipitation and high evaporation. The geological structure is dominated by sandy loams, sands, and carbonate deposits with high permeability. Under such conditions, most atmospheric precipitation infiltrates into deep soil horizons, accumulates in local depressions, and rapidly evaporates under high summer air temperatures. As a result, even heavy rainfall does not lead to an increase in channel runoff; on the contrary, it reduces its volume because the water balance shifts toward irreversible losses (Andersson *et al*., 2001; Scanlon *et al*., 2006). Minimum river discharge, particularly in arid basins, should be regarded as an inertial component of the water regime, shaped by long-term accumulation, infiltration, and groundwater recharge, rather than by an immediate response to current precipitation.

As noted in a number of international studies (Shanafield, 2021; Birimbayeva *et al*., 2024), under arid climate conditions, there is often a time lag between precipitation events and river discharge. In summer, intense rainfall is accompanied by high evaporation and deep infiltration, so actual runoff may not increase and in some cases may even decline due to falling groundwater levels and downward drainage of soil moisture (Goodrich, 2004).

In continental climates with prolonged sub-zero temperatures in winter, small rivers often freeze to the channel bed, effectively halting water movement. Precipitation falling as snow accumulates in the snowpack but does not contribute to current discharge formation, which makes the correlation between winter precipitation and runoff not only weak but, in some cases, negative. Moreover, snow accumulation can aggravate channel blockages by ice crusts and icings, further restricting already limited winter flow (Woo, 2008).

Anthropogenic influences cannot be ruled out either. During low-water years, precipitation events may trigger intensified water use for agriculture (e.g., filling ponds, irrigation), leading to redistribution of water resources and a reduction in river discharge available downstream (Falkenmark & Rockström, 2006).

The negative relationship between precipitation and minimum discharge in the Karatorgay and Torgay basins can thus be explained by a combination of factors:

- high infiltration capacity of soils, causing water to be retained in subsoil horizons;
- dominance of evaporation over runoff generation;
- inertial character of low-flow formation, with weak dependence on short-term meteorological conditions;
- deep channel freezing in winter, excluding precipitation from runoff formation;
- possible human interventions in water use following precipitation events.

These findings highlight the importance of an integrated approach to analyzing river flow response to climatic signals, especially in arid and semi-arid regions where the classical "precipitation–runoff" relationship does not always operate in a straightforward positive direction (Wheater & Evans, 2009).

Climatic contrasts in dry and wet years

A comparative analysis of climate–hydrological relationships depending on interannual water availability revealed qualitatively different regimes of low-flow formation. Separate assessments of climatic controls in wet years ($P \leq 0.25$ quantile) and dry years ($P \geq 0.75$ quantile) demonstrated significant differences in the governing factors.

In dry years, the role of precipitation decreases, while the influence of temperature becomes more pronounced, especially the temperatures of the preceding warm season. For example, at the Toguzak River gauging station (winter flow), a positive correlation was identified between the previous warm-season temperature and low-flow discharge ($R \approx 0.5$). This may reflect prolonged recharge of groundwater under high evaporative demand and subsequent transformation of the water balance.

In wet years, the role of precipitation mainly during the warm season increases. This reflects a more direct response of river flow to meteorological conditions under:

- sufficient soil moisture saturation;
- the presence of active surface drainage;
- reduced infiltration and evaporation losses.

However, for several rivers, such as the Torgai and Kara-Torgai, earlier studies assumed a strong positive correlation between summer precipitation and minimum flow (up to $R \approx 0.6$). A later re-examination of the data, however, indicated that actual correlation coefficients remain at weak to moderate levels ($R < 0.4$), and in some cases even show a negative sign. This points to the nonlinearity and instability of precipitation–low flow relationships, even in water-abundant years, which may be linked to infiltration capacity of the catchment and landscape-related water storage processes (Scanlon *et al*., 2006).

In dry years, the role of precipitation decreases markedly, while temperature becomes the dominant factor. Of particular importance is the temperature of the preceding warm season, which affects soil moisture losses through evaporation, groundwater dynamics, and the degree of watershed desiccation.

For example, at the Toguzak hydrological station (winter discharge), a moderate positive correlation ($R \approx 0.5$) was found between the mean temperature of the previous warm season and the minimum winter flow. This likely reflects enhanced infiltration and groundwater storage under high evaporative demand, which in turn supports a more stable subsurface contribution to winter discharge despite weak surface inflow (Shanafield, 2021).

Overall, in wet years, minimum discharge responds more directly to precipitation, especially summer rainfall if surface drainage remains active. In contrast, in dry years, climatic control shifts towards temperature, which governs potential moisture losses and redistribution within the catchment. This suggests that modeling and forecasting of low-flow conditions should differentiate between wet and dry years, accounting for seasonal water balance and the phase state of available resources.

These contrasts illustrate a dynamic nonstationarity of flow-controlling factors: in water-deficient years, the thermal regime and antecedent moisture storage are critical, while in wetter years, the flow regime is driven mainly by the amount and timing of rainfall.

The findings highlight the need to incorporate climate-related variability into predictive models and adaptation strategies for water management. They are consistent with results reported in a number of international studies (Kundzewicz *et al*., 2008; Belyaev *et al*., 2019), which show an increasing influence of air temperature on river discharge under global warming, particularly where precipitation is uneven, and evaporative demand is high. Similar trends have been documented in other regions (Kundzewicz *et al*., 2008; Shiklomanov & Lammers, 2020; Birimbayeva *et al*., 2024; Makhmudova *et al*., 2024; Smagulov *et al*., 2025), where changes in the thermal regime are driving a reorganization of river flow (Agrawal *et al*., 2024; Bona & Lozano, 2024; Khan *et al*., 2024; Ha *et al*., 2025; Yilmaz & Erkol, 2025).

This study contributes to the regional understanding of climate control on river discharge under continental climate and steppe landscapes. A key finding is the spatial–seasonal variability of climate sensitivity, where the dominant factors, such as temperature or precipitation, change not only vary with the season but also with geographic location and catchment water availability (Danchin *et al*., 2024, Essah *et al*., 2024; Hillman, 2024; Qiao *et al*., 2024; Rivera & Carter, 2024; Snodin & McCrossen, 2024; Souza *et al*., 2024; Braun *et al*., 2025; Cuenca-Martínez *et al*., 2025; Eid *et al*., 2025).

Particularly noteworthy are the contrasts between dry and wet years, which are rarely addressed in international studies focusing mainly on averaged conditions. This approach allows for a more detailed understanding of hydrological responses to extreme climatic events and improves the realism of regional hydrological forecasts. The results provide an empirically based complement to global climate–hydrology models, highlighting the specific characteristics of steppe river systems in Central Asia and Eastern Europe.

The homogeneity of low-flow time series is critical for accurate statistical modeling, hydrological forecasts, and water resource assessment. Structural breaks may reflect changes in climate, hydrotechnical interventions, or anthropogenic impacts. Steppe and semi-arid regions of Central and Northern Kazakhstan are particularly sensitive, as runoff is episodic and strongly dependent on meteorological conditions (Pettitt, 1979; IPCC, 2021).

To assess homogeneity, the following methods were applied: parametric tests—Student's *t*-test (for mean differences) and Fisher's *F*-test (for variance differences); non-parametric tests—Mann–Whitney *U*-test (for differences in distributions). All calculations were performed using Python with the SciPy Stats package. The significance level was set at $\alpha = 0.05$. The results indicate substantial differences in runoff structure before and after identified breakpoints:

1. Toguzak River – Toguzak station (summer 1989 / winter 1992): sharp decline in mean values after 1989; $t = -2.18$ ($p = 0.034$) for summer, $t = -6.53$ ($p = 1.5e-7$) for winter. Mann–Whitney *U*-test also gave $p < 0.01$ for both series.
2. Tobyl River – Grishenka station (summer 1985 / winter 1976): after 1985, discharge amplitude and variability increased; summer $t = -3.56$ ($p = 0.00075$), winter $t = -3.92$ ($p = 0.00032$).
3. Tobyl River – Kostanay station (summer 1989 / winter 1988): following structural shifts, discharge increased multiple times (up to 10–21 m^3/s), likely influenced by reservoir releases.
4. Ayat River – Varvarinka station (summer 1992): a clear shift toward higher flows; $t = -3.92$ ($p = 0.00042$), $U = 261.5$ ($p < 1e-4$).
5. Karatorgay River – Urpek station (summer 1981): after 1981, over 60% of summer observations recorded zero flow, supporting the hypothesis of full channel freezing in winter–spring and high sensitivity to climatic fluctuations; $t = 2.89$ ($p = 0.005$).
6. Torgay River – Peski Tusum (summer 1965): abrupt cessation of flow after 1965. Between 1981 and 2020, some years recorded a complete zero flow, likely due to increased evaporation, reduction in meltwater contributions, and retention of precipitation in soils; $t = 2.40$ ($p = 0.023$), $U = 1108.0$ ($p \approx 2e-8$).

The results confirm runoff heterogeneity across almost all studied rivers. Possible contributing factors include:

- climatic shifts, particularly rising winter temperatures;
- reduced duration of persistent snow cover;
- changes in summer precipitation patterns;
- hydraulic regulation, especially on the Tobyl River, where increased discharges are associated with reservoir operations;
- anthropogenic degradation, including floodplain cultivation, altered filtration regimes, and reduced soil water retention capacity.

Similar findings regarding the impact of climatic fluctuations on runoff homogeneity are reported in previous studies (IPCC, 2021; Kundzewicz *et al*., 2008). In Central and Northern Kazakhstan, the homogeneity of river discharge series has been disrupted by the combined effects of climatic and anthropogenic factors. Statistical tests (Student's *t*-test, Fisher's *F*-test, Mann–Whitney *U*-test) confirmed the presence of structural breaks, particularly for rivers with seasonal or episodic flows. Future hydrological models should consider phase-based segmentation of time series according to breakpoints, modeling each regime separately, and taking into account winter low-flow degradation as an indicator of climate vulnerability.

Stationarity analysis of low-flow time series

Low-flow time series were tested for stationarity using two widely applied methods:

- ADF (Augmented Dickey-Fuller) – tests the null hypothesis of a unit root, indicating non-stationarity. If $p < 0.05$, the null hypothesis is rejected and the series is considered stationary (Said & Dickey, 1984).
- KPSS (Kwiatkowski–Phillips–Schmidt–Shin) – unlike ADF, tests the null hypothesis of stationarity around a level. If $p < 0.05$, the null is rejected, and the series is considered non-stationary (Kwiatkowski *et al.*, 1992).

The two tests complement each other: ADF detects trends or drifts, while KPSS evaluates the stability of the level. The results are summarized in **Table 3.**

The summer low-flow series of the Toguzak River was found to be stationary according to both tests, allowing the use of standard modeling approaches without additional transformation. In contrast, the winter low-flow series of the same river was non-stationary by both tests, indicating a persistent trend and a possible structural shift.

In some cases, discrepancies between the tests were observed. For example, at the Tobyl River – Grishenka station (winter period), the series was stationary according to the ADF test but non-stationary according to KPSS, suggesting a phase shift in mean values while the autocorrelation structure remains largely intact.

Low-flow series for the Ayat, Karatorgay, and Torgay rivers also exhibited unstable behavior, with ADF failing to reject the null hypothesis of non-stationarity while KPSS confirmed it. This highlights the need for caution when analyzing trends. Overall, most series, particularly for the winter period, show signs of non-stationarity, which should be taken into account when developing predictive models, assessing water availability, or calculating normative flows. Under such conditions, the use of adaptive models or prior transformation of the series (e.g., differencing) is justified.

Table 3. Stationarity of minimum flow time series in the Tobyl–Torgay river basin

№	River – Observation point	Season	ADF statistic	p-ADF	KPSS statistic	p-KPSS	Interpretation
1	Toguzak – s. Togyzak	Summer	−3.57	0.0063	0.1726	0.1	The time series is stationary by both tests.
2		Winter	−1.36	0.6014	0.7504	0.01	The time series is non-stationary by both tests.
3	Tobyl – s. Grishenka	Summer	−2.94	0.0403	0.2556	0.1	The time series is stationary by both tests.
4		Winter	−4.11	0.00094	0.5579	0.0286	Stationary by ADF, non-stationary by KPSS
5	Tobyl – Kostanay	Summer	−2.65	0.0837	0.5388	0.0329	The time series is non-stationary by both tests.
6		Winter	−7.17	0.0000003	0.7224	0.01	The time series is non-stationary by both tests.
7	Ayat – s. Varvarinka	Summer	−4.21	0.00063	0.2831	0.1	The time series is non-stationary by both tests.
8	Kara-Torgay – s. Urpek	Summer	−4.14	0.00081	0.6851	0.015	The time series is non-stationary by both tests.
9	Torgay – Peski Tusum	Summer	−1.94	0.312	0.7078	0.0128	The time series is non-stationary by both tests.

To evaluate the direction of changes in low flows, a linear trend analysis based on 10-year moving averages was performed **(Figure 3).** This approach allows the identification of persistent trends by smoothing short-term fluctuations and highlighting long-term changes in the hydrological regime. The analysis was conducted separately for summer and winter periods.

Summer period

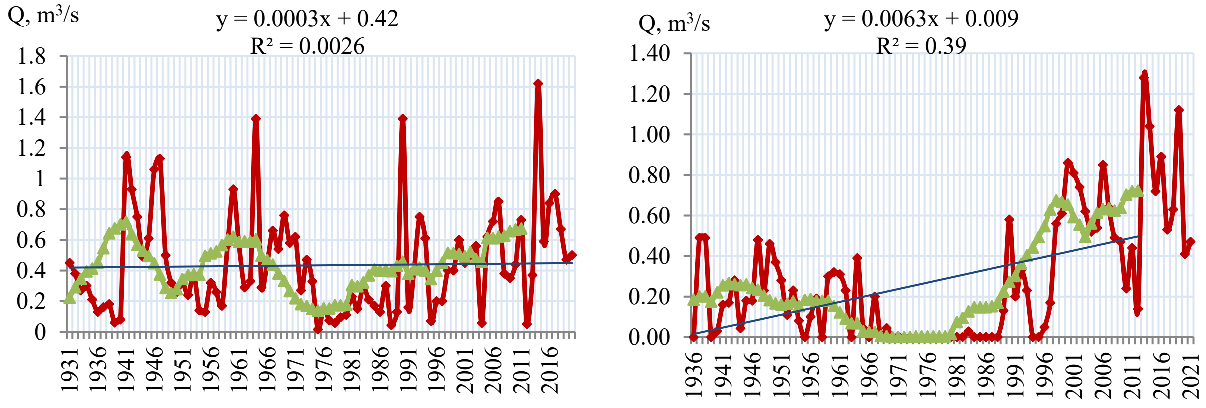
For the summer low flow of the Toguzak River – Togyzak station, the 10-year moving average analysis revealed a slight positive change. The average growth rate was approximately 0.0003 m^3/s per year. However, the coefficient of determination (R^2 = 0.026) indicates very low explanatory power and statistical reliability. Therefore, the observed trend is not statistically robust and likely reflects short-term fluctuations rather than a systematic change in river regime.

Tobyl river – Grishenka station

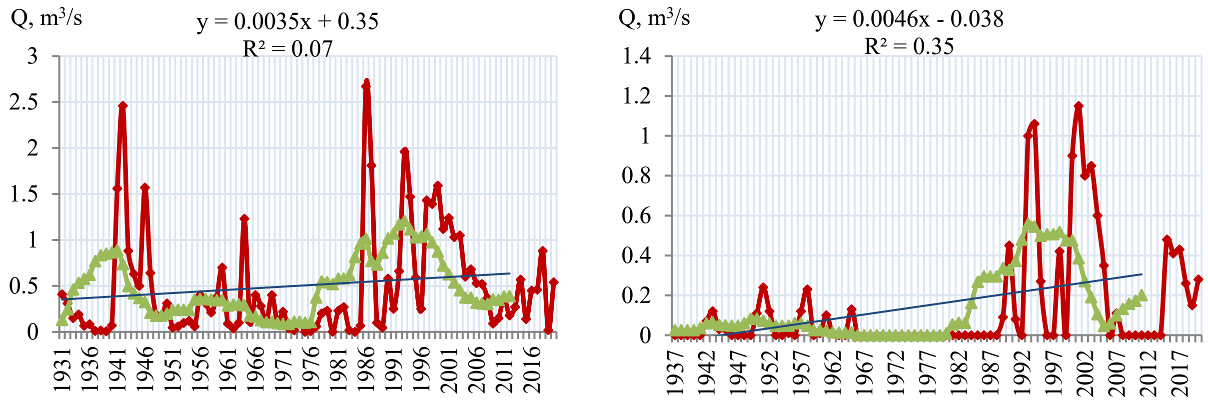
For the summer period, a more pronounced positive trend was detected, with an increase of about 0.0035 m^3/s per year. Despite the relatively low R^2 (~0.07), this indicates a consistent increase in discharge, possibly linked to the recurrence of warm-season precipitation and local catchment characteristics.

Tobyl River – Kostanay.

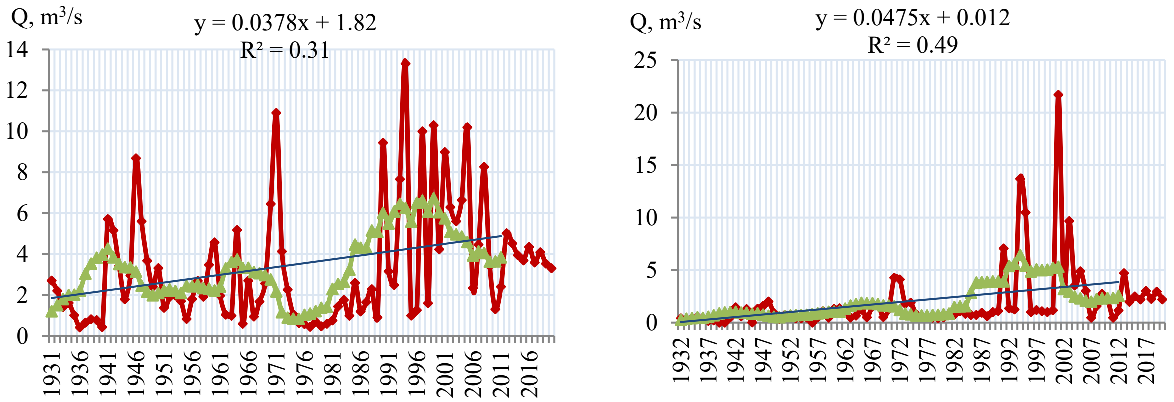
At this site, a moderate increase in summer low flow was recorded, with an average growth rate of 0.04 m^3/s per year. The coefficient of determination exceeds 31 %, confirming the presence of a stable trend. The observed behavior is likely influenced by reservoir regulation, which helps maintain minimum flows during summer by smoothing seasonal fluctuations.



(a) Toguzak – s. Togyzak



(b) Tobyl – s. Grishenka



(c) Tobyl – Kostanay

Figure 3. Dynamics of minimum flow changes in the rivers of the Tobyl basin

Winter period

The winter low flow of the Toguzak River – Togyzak station shows a pronounced and consistent increase, with an average growth rate of 0.063 m^3/s per year. The coefficient of determination is nearly 40 %, indicating a strong statistical basis. These changes can be interpreted as resulting from climate warming, reduced riverbed freezing, and enhanced groundwater contributions.

Analysis of the Tobyl River – Grishenka station revealed a steady increase in winter low flow at a rate of 0.046 m^3/s per year. The coefficient of determination is 0.345, meaning that approximately 35 % of the variability in minimum flows can be explained by the linear trend, indicating moderate stability. The increase in winter low flows is likely associated with gradual warming, manifested as higher average air temperatures, reduced soil and riverbed freezing, and enhanced groundwater supply at the end of winter. Such processes are possible even under harsh climatic conditions due to the accumulated thermal background and extended transitional temperature periods.

The highest trend stability among all studied sites is observed at the Tobyl River – Kostanay section. Winter low flow increases on average by 0.048 m^3/s per year, with a coefficient of determination approaching 50 %, confirming a systemic shift to a new hydrological regime. In addition to the climatic factor, reservoir regulation significantly affects the flow regime, smoothing seasonal variability and maintaining minimum flows even during winter months. The results of this study complement existing scientific knowledge, emphasizing the need to consider regional features of climate–hydrology interactions when developing adaptive water management strategies under changing climate conditions.

CONCLUSION

Through an extensive examination of longitudinal data concerning minimum river flows alongside climate observations gathered from the Kostanay meteorological station, significant alterations in the thermal and hydrological patterns of northern Kazakhstan were discerned, particularly throughout the 1980s and 1990s. The most notable changes were detected in air temperatures during the cold season, which exhibit a consistent rise at a rate reaching +0.049 °C annually, corroborated by elevated R² values and trends that are statistically significant ($p<0.01$).

The analysis of climate–hydrology relations identified minimum flows in winter as mainly controlled by air temperature because it affects soil freezing depth, infiltration for meltwater, and recharge for groundwater. Precipitation is involved secondarily when it comes into play under moisture-accumulation-sufficient conditions, like wet winters.

For warm-period conditions in the summertime, warm-period atmospheric precipitation is the dominant controller of minimum flow, highlighting the importance of rainfall at the immediate surface for sustaining low flows. Temperature effects are less certain: positive (via increased snowmelt and recharge for groundwater stores) or negative (via increased evaporation and less efficient runoff). Interannual variations in climatic responsiveness in arid and wet years were identified as requiring consideration in integrated water resources management. A comparative analysis across interannual flow conditions indicated that the climatic influence on flow framework is characterized by dynamic non-stationarity: in arid years, temperature is dominant (explaining about 50–60%), while in wet years, precipitation and stored water reserves become increasingly important. That is why hydrological assessments need to consider spatiotemporal differentiation.

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