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Reaction of Minimum Streamflow of Arid Kazakhstan Rivers to Climate Non-Stationarity

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Abstract

This article provides a comprehensive analysis of long-term changes in the minimum river flow of the southern rivers of Western Kazakhstan (Temir, Oiyil, Zhem) for the period 1940–2022, with an emphasis on summer minimum and winter low flow as key indicators of water and environmental sustainability in conditions of increasing climate variability. The study combines a typology of the climate control mechanisms of minimum flow, analysis of structural homogeneity, and assessment of the internal organization of time series based on ITA and the integral IPTA method, which allow us to reveal the hidden fluctuations and stable phase states of the hydrological regime. The calculation of the climate sensitivity index (CSI_{min}) showed pronounced seasonal asymmetry: summer runoff is largely controlled by atmospheric precipitation, while winter minimum runoff is determined by temperature regime and soil freezing depth. Parametric and nonparametric tests (Pettitt, ADF, SNHT) revealed significant structural shifts in the 1960s–1990s period, corresponding to large-scale climatic anomalies in the region. Summer series are characterized by phases of prolonged low water levels and negative trends in the mid-20th century, while for the winter period, a steady increase in minimum flow has been established, due to regional warming and an increase in the share of underground recharge. IPTA confirmed the presence of long-term phases with high internal heterogeneity in the summer season and a more stable winter runoff structure. The results demonstrate the high climatic sensitivity of minimum runoff and confirm the need to move from static standards to dynamically adaptable methods of water resource assessment. The proposed approach can serve as a tool for developing adaptation strategies, assessing the risk profile of basins, and improving the sustainability of water management planning in arid regions.

Keywords: minimum discharge; climatic sensitivity; structural shifts; climate management typology; seasonal variability; climate impact

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1. Introduction

Minimum river flow is a key indicator of the sustainability of hydrological systems, especially in arid regions, where a decrease in low-flow water directly reflects the response of watersheds to climate change and anthropogenic impacts. In conditions of increasing climate variability, it is precisely the minimum summer flow and winter low flow that are the most sensitive characteristics of water resources, responding to changes in temperature regime, precipitation redistribution, frost depth, and the state of groundwater recharge. Recent studies have noted a trend toward more frequent low-flow periods, shorter natural low-flow periods, and more complex intra-seasonal flow dynamics, creating a need for flexible analytical methods to diagnose structural changes [1,2].

The changes in low flow observed around the world highlight the heterogeneous nature of hydrological responses. In the basins of Central Europe, alternating periods of extreme low water are recorded [3], while in East Asian and Oceanic regions, there is an increase in low-flow conditions in the context of warming [4]. Steppe and semi-arid zones, on the other hand, are characterized by steady downward trends in summer Q_{min} against a backdrop of aridization. Recent studies of water systems [5,6] demonstrate the need to transition to adaptive methods of analysis and forecasting that take into account climatic non-stationarity and the complex internal organization of time series. These approaches are particularly relevant for small rivers in the southern part of Western Kazakhstan, where minimum flow is influenced by both seasonal climatic fluctuations and the characteristics of geomorphology and underground recharge.

Issues of low-water and low-flow conditions are actively studied in domestic [7–12] and foreign scientific literature [13–19]. Thus, research by [20] showed an increase in seasonal asymmetry and a reduction in summer low-flow conditions in the European part of Russia. The work of [21] emphasizes the key role of atmospheric precipitation in the formation of low-water river regimes, especially in conditions of climatic instability. At the global level, the study of water deficits is considered in the context of climate warming: according to the World Meteorological Organization [2], changes in low-water characteristics are becoming more pronounced, especially in arid and semi-arid regions. Individual studies [1] focus on the intensification of low water levels as one of the most important manifestations of the climatic transformation of hydrological systems, emphasizing the need to develop adaptive water management strategies.

The methodological aspects of analyzing structural changes in hydrological time series have been developed since the classic work by [22], which proposed a criterion for simultaneous detection of a break without prior knowledge of the moment of its occurrence. Subsequently, the analysis methods have been refined, including non-parametric approaches to assessing sustainable changes under conditions of climate non-stationarity [3,4,22–25]. Among them, the Mann–Kendall test, SNHT, and the visual analysis of integral deviation curves are of particular importance. Given the inadequacy of classical analysis methods (linear trends, homogeneity criteria, point break tests), there is a growing need for techniques capable of identifying both external structural changes and the hidden internal organization of time series [26,27]. The nonparametric Pettitt criterion, ADF and SNHT tests allow us to establish breakpoints and assess stationarity, but they do not reflect the internal phase structure of minimum flow [28]. In this regard, both ITA (Intermediate Trend Analysis) and its integral modification IPTA have been used; they can identify successive phases of low water and relatively favorable periods, diagnose the anisotropy of minimum flow, assess the length and amplitude of structural states, and identify stable climate-driven fluctuations [29–31].

An important component of minimum flow analysis is the typology of climate control, for which the climate sensitivity index CSI_{min} is used in this study. This index reflects the

predominant role of temperature or precipitation in the formation of minimum flow and allows climate control to be classified as precipitation, temperature, or mixed [32]. This approach makes it possible to take into account seasonal asymmetry: in summer, the minimum flow of southern rivers in Western Kazakhstan is mainly controlled by atmospheric precipitation, while in winter it is controlled by temperature conditions and the depth of soil freezing. The integration of control typology, structural tests, and ITA/IPTA methods forms a comprehensive methodological basis for identifying climate-driven transitions in the hydrological system and assessing its adaptive resilience.

Despite the wide application of these methods in hydrological studies, their integrated use for diagnosing the phase–integral organization of minimum flow regimes in arid river basins remains limited. In particular, the long-term minimum flow dynamics of small and medium-sized rivers in Western Kazakhstan have not been previously analyzed from the perspective of phase structure, regime shifts, and climatic non-stationarity. The present study addresses this gap by implementing a unified methodological framework that combines breakpoint detection, stationarity assessment, climate sensitivity typology, and phase–integral analysis of time series.

This study conducts a multifaceted analysis of the minimum summer and winter runoff of the Temir, Oiyil, and Zhem rivers for the period 1940–2022. The aim of the study is to identify long-term trends in minimum flow, determine moments of structural shifts, assess the climate sensitivity of systems, and investigate the internal organization of time series using ITA/IPTA. The scientific novelty of the work lies in the systematic analysis of changes in minimum flow, which identifies long-term stable regimes and distinguishes them from short-term variability in conditions of climatic instability. The results obtained are aimed at clarifying the mechanisms of formation of meanders in conditions of climatic non-stationarity and can be used to develop adaptation strategies for water use in arid regions.

2. Materials and Methods

2.1. Study Area

Western Kazakhstan is located in an arid zone between Eastern Europe and Central Asia. The region is characterized by a sharply continental climate with low precipitation (180–300 mm/year) and high potential evaporation (up to 800–1000 mm/year), which creates a persistent negative water balance.

The Temir, Oiyil, and Zhem river basins under study are located in the central part of the arid zone (Figure 1).

The rivers have a pronounced snow-fed regime: a short spring flood is formed by the melting of snow cover, and in summer and winter, the flow is either minimal or completely absent. Summer–autumn low water flow occurs only in exceptionally wet years.

The alluvial valleys of the basins are composed of sands, sandy loams, and loess rocks with high filtration capacity. A significant part of the flood runoff is infiltrated, which makes watercourses extremely sensitive to long-term aridization and the drying up of riverbeds. These features determine the high dependence of minimum runoff on climatic conditions and the state of groundwater.

The Temir river flows through slightly dissected accumulative plains with minimal soil water capacity; Oiyil is characterized by a more developed underground drainage system; Zhem is one of the most arid basins in the region and has a consistently low minimum flow. The analysis uses data for 1940–2022 from the Lensky, Taltogay, and Zarkamys hydrological stations on the Temir, Oiyil, and Zhem rivers, respectively, including a continuous series of minimum summer (July–August) and winter (January–February) runoff.

The region is characterized by low water availability, high climatic sensitivity, and a significant role of filtration losses, which makes it an optimal object for studying structural changes in minimum flow. An additional factor of water management load is individual oil and gas developments, especially in the Zhem river basin.

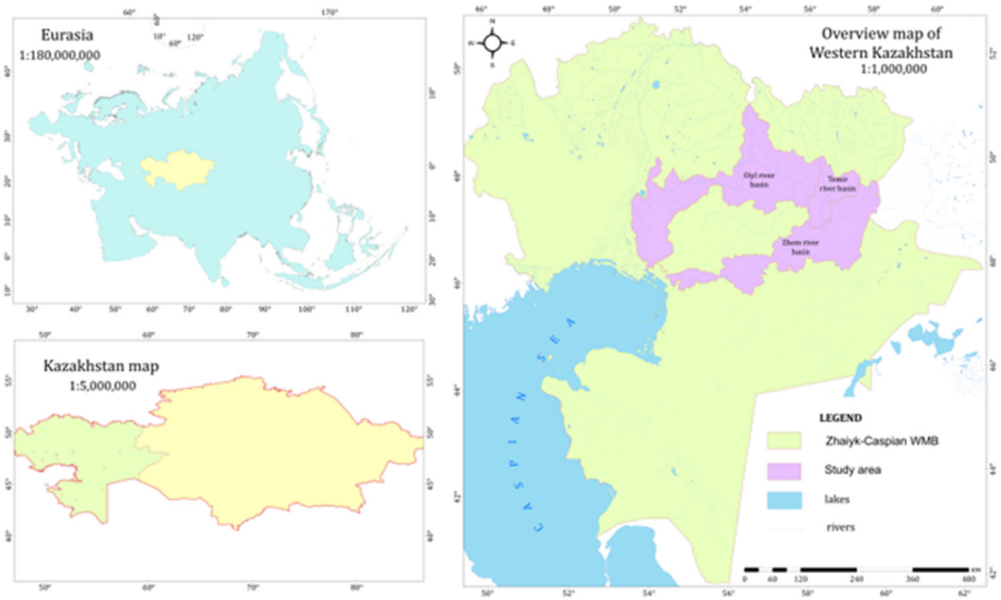

Figure 1. Overview map of Western Kazakhstan.

2.2. Hydrological and Climatic Data

The study used long-term series of minimum river flow and climatic parameters for the period 1940–2022. Minimum flow was defined as the lowest average monthly water consumption in the summer (July–August) and winter (January–February) seasons. Hydrological data were obtained from the following hydrological stations and locations and underwent basic control processing: Lensky, Temir river; Taltogay, Oiyil river; and Zharkamys, Zhem river.

Climatic parameters include average seasonal air temperature and total seasonal precipitation calculated based on data from the Temir, Oiyil, and Zhem weather stations. Seasonal values were calculated using standard Kazhydromet methods, ensuring temporal consistency between hydrological and meteorological series.

All source data were obtained from the official open resources of RSE Kazhydromet [33]. The length and continuity of the observations allow for the analysis of the structural changes, seasonal differences, and climatic determinants of minimum flow.

2.3. Research Methods

To achieve the set goals, a set of modern time series analysis methods widely used in hydrological practice and recommended by leading scientific schools [22,34–38] were used. These tools allowed us to identify structural shifts, check the stationarity and homogeneity of the series, and to determine the presence of stable trends and long-term fluctuations.

2.3.1. Structural Shifts and Homogeneity

To identify long-term changes in minimum flow, a comprehensive analysis of the homogeneity and the structural shifts of the time series was performed. The main tool for detecting breaks was the nonparametric Pettitt criterion, which allows determination of the year of transition of the hydrological system to a new state when climatic conditions change.

To confirm the statistical significance of the differences between the subsamples before and after the breakpoint, parametric and nonparametric tests were applied: Student's *t*-test (change in means), Fisher's F-test (change in variances), the Mann–Whitney U-test, and the Wilcoxon test (change in distributions). The combined use of these tests provides a reliable diagnosis of heterogeneity and allows us to differentiate changes in the level, spread, and distribution shape of minimum flow.

A similar analysis was performed for the climatic parameters (temperature and precipitation), which made it possible to compare hydrological breaks with climatic phases and assess the consistency of climate–runoff interaction.

Verification of the homogeneity of the time series using the *t*-test, F-criterion, U-test, and Wilcoxon criterion confirmed statistically significant differences in the mean values in most cases, while maintaining variance, which is characteristic of climatically induced changes in runoff levels.

The identified structural shifts and confirmed heterogeneity of the series (Table 1) form the basis for the next stage of analysis—assessing the direction of long-term changes using trend models.

Table 1. Structural changes in minimum runoff and climatic parameters.

Object of Analysis	Parameter	Season	Year of Structural Shift	U-Statistics	*p*-Value	Statistical Significance
Temir River—Lensky Village	Q_{min}	Summer	1967	1007.0	0.000054	Significant gap
		Winter	1991	911.0	0.00037	Significant gap
Oiyil River—Taltogay Village		Summer	1981	768	0.0044	Significant change
		Winter	1985	883.0	0.0006	Significant gap
Zhem River—Zharkamys Village		Summer	1991	603.0	0.027	Significant change
		Winter	1989	926.0	0.00028	Significant gap
MS Temir	T, °C	Summer	1995	1086.0	0.00014	Significant gap
		Winter	1980	1032.0	0.00026	Significant gap
	P, mm	Summer	2007	492.0	0.279	Shift not confirmed
		Winter	1970	1197.0	0.00002	Significant gap
MS Oiyil	T, °C	Summer	1981	438.0	0.398	Shift not confirmed
		Winter	1961	556.0	0.148	Shift not confirmed
	P, mm	Summer	1944	407.0	0.519	Shift not confirmed
		Winter	1955	989.0	0.00053	Significant gap
MS Zhem	T, °C	Summer	1975	1328.0	0.00001	Significant gap
		Winter	1977	753.0	0.014	Significant change
	P, mm	Summer	2006	384.0	0.434	Shift not confirmed
		Winter	1970	1178.0	0.00002	Significant gap

The final results of the analysis of the homogeneity of minimum summer and winter runoff for all three rivers are presented in Table 2.

Table 2. Results of the analysis of the homogeneity of time series of minimum flow for the Temir, Oiyil, and Zhem rivers.

Water Body	Season	Student's *t*-Test (for Difference in Means)	Fisher's F-Test (for Differences in Variances)	Wilcoxon Signed-Rank Test (Nonparametric Test)	Mann–Whitney U-Test (Test for Differences Between Samples Based on Rank Characteristics)
Temir River	Summer	0.000031	0.0354	0.0000013	0.0000054
	Winter	0.00018	0.9998	0.00075	0.00030
Oiyil River	Summer	0.00197	0.998	0.00021	0.00059
	Winter	0.0023	0.0519	0.0027	0.0015
Zhem River	Summer	0.039	1.54	0.048	0.021
	Winter	0.0060	0.994	0.013	0.0071

Certain moments of structural shifts and the identified heterogeneity of the time series require further quantitative assessment of the direction of changes, which is performed within the framework of trend analysis.

2.3.2. Trend Analysis

To assess the direction and intensity of long-term changes in minimum flow, a trend analysis was performed based on a combination of linear regression models and smoothing

methods. The linear trend is determined by a simple regression equation, where the slope coefficient reflects the average rate of change in Qmin over the entire observation period, allowing for a quantitative assessment of its long-term dynamics. Interdecadal variations were identified using moving averages and moving trends, which suppress short-term fluctuations and allow stable phase trends to be identified (Figure 2). This approach is particularly important in conditions of climatic non-stationarity, when the direction of flow changes can vary significantly between periods.

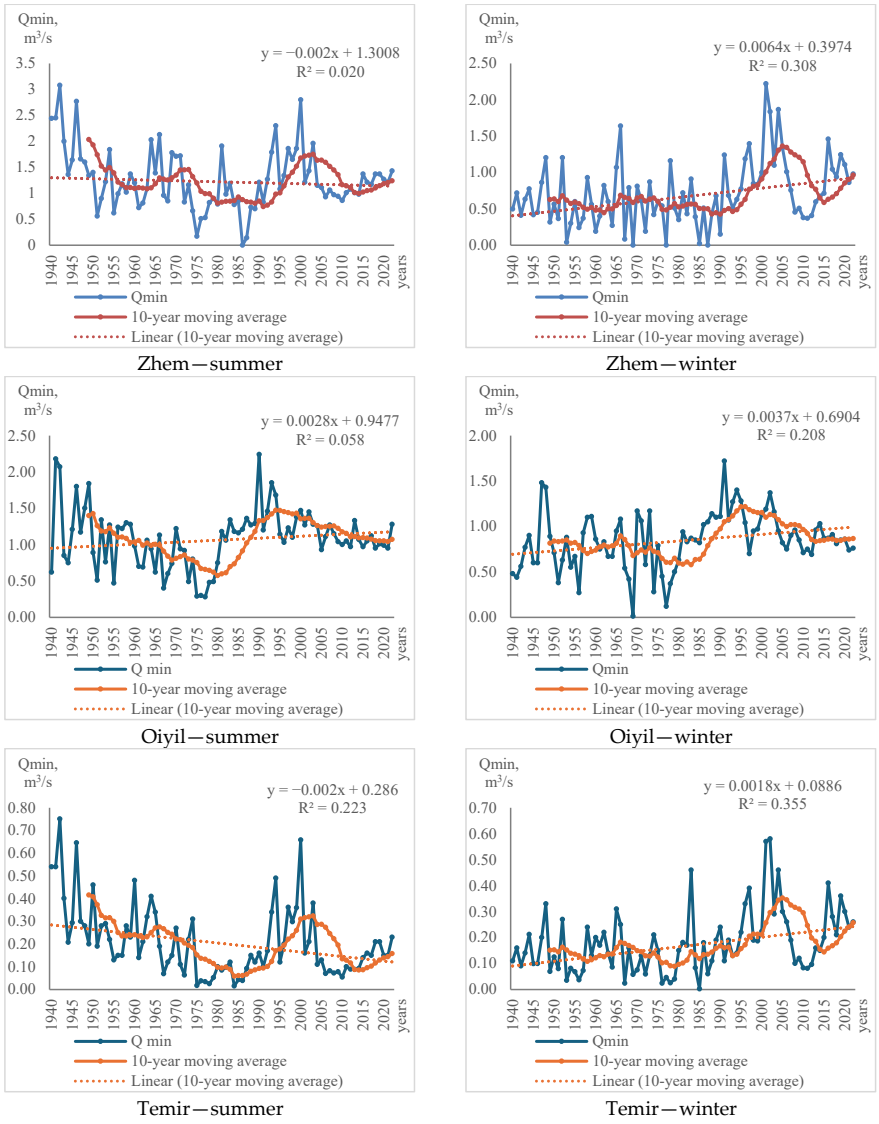

Figure 2. Linear and moving trends of minimum summer and winter runoff (Q_{min}) of the Temir, Oiyil, and Zhem rivers.

A parallel analysis of climatic parameters (temperature and precipitation) was performed using an identical scheme, which ensured the comparability of climatic and hydrological trends and allowed us to link changes in minimum runoff with the long-term evolution of climatic conditions.

2.3.3. ADF Stationarity Test

To assess the temporal stability of the minimum flow and climatic parameters, the Augmented Dickey–Fuller (ADF) test was used, which allows the determination of the presence of a unit root and the order of integrability of a time series [39]. The ADF approach

is widely used in hydrology and climatology to analyze changes caused by climatic non-stationarity.

The test is based on an evaluation of Equation (1):

$$\Delta y_t = \alpha + \beta t + \gamma y_{t-1} + \sum_{i=1}^{\rho} \delta_i \Delta y_{t-i} + \varepsilon_t \quad (1)$$

where $\Delta y_t = y_t - y_{t-1}$ is the increment; γ is the coefficient at the lag value; ρ is the number of lags; ε_t is the error.

The null hypothesis assumes non-stationarity of the series, while the alternative hypothesis assumes stationarity. Lag differences compensate for autocorrelation, ensuring correct statistical testing. Comparison of $\tau_a$df with McCann's critical values (5% significance level) allowed for reliable classification of the time series.

The test was performed for minimum summer and winter runoff, as well as seasonal temperatures and precipitation (Table 3). The test results determine the possibility of further use of regression methods: stationary series allow direct modeling, while non-stationary series require careful interpretation and consideration of structural shifts.

Table 3. Assessment of the stationarity of time series of minimum runoff and climatic parameters (ADF test).

River/Weather Station	Period	Parameter	ADF Statistics	*p*-Value	Critical Value (5%)	Conclusion on Stationarity
Temir	Summer	Q_{min}	−2.34	0.16	0.05	Non-stationary
	Winter		−5.36	0.000004	0.05	Stationary
Oiyil	Summer		−2.73	0.06	0.05	Almost stationary
	Winter		−2.41	0.14	0.05	Non-stationary
Zhem	Summer		−5.19	0.000009	0.05	Stationary
	Winter		−2.88	0.047	0.05	On the verge
MS Temir	Summer	T, °C	−3.16	0.022	0.05	Stationary
	Winter		0.75	0.833	0.05	Non-stationary
	Summer	P, mm	−7.98	2.64×10^{-12}	0.05	Stationary
	Winter		−2.15	0.225	0.05	Non-stationary
MS Oiyil	Summer	T, °C	−8.01	2.27×10^{-12}	0.05	Stationary
	Winter		−8.33	1.06×10^{-13}	0.05	Stationary
	Summer	P, mm	−9.27	1.34×10^{-15}	0.05	Stationary
	Winter		−4.29	0.0005	0.05	Stationary
MS Zhem	Summer	T, °C	−4.58	0.00014	0.05	Stationary
	Winter		−5.52	1.09×10^{-6}	0.05	Stationary
	Summer	P, mm	−4.66	0.0001	0.05	Stationary
	Winter		−2.13	0.233	0.05	Non-stationary

The obtained estimates of stationarity refine the temporal structure of the minimum flow and climatic parameters and also form the basis for analyzing climatic sensitivity within the framework of the CSI_{min}.

2.3.4. Minimum Flow Climate Sensitivity Index (CSI_{min})

To quantitatively assess the impact of the climatic factors on the formation of minimum flow, an integral climate sensitivity index (CSI_{min}) is used, reflecting the relative contribution of air temperature and seasonal precipitation to the interannual variability of Qmin [32]. The index allows us to determine the dominant type of climate control and track its seasonal specifics. CSI_{min} is determined by Equation (2):

$$CSI_{min} = \frac{r(Q_{min}, T) - r(Q_{min}, P)}{r(Q_{min}, T) + r(Q_{min}, P)} \quad (2)$$

where $r(Q_{min}, T)$ is the correlation coefficient of minimum flow with air temperature and $r(Q_{min}, P)$ is the correlation coefficient between minimum flow and precipitation.

Positive values reflect temperature control, negative values reflect precipitation control, and values close to zero indicate a balanced influence of both factors. This approach allows us to identify seasonal asymmetry in climate control: in arid basins, summer Qmin is

usually determined by precipitation, while winter Qmin is determined by temperature and frost depth (Figure 3).

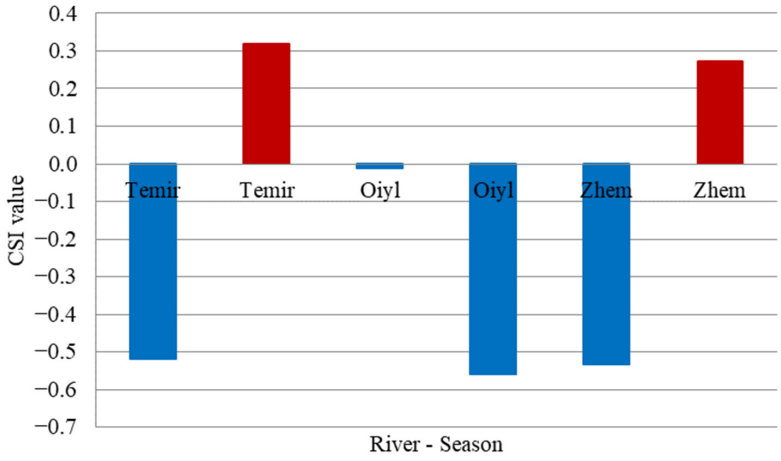

Figure 3. Typology of climate sensitivity (red–positive values, blue–negative values).

The index is used for inter-basin comparison, diagnosis of climate-induced changes, and comparison with the internal structure of the series identified by the ITA/IPTA methods used in subsequent sections.

2.3.5. ITA (Intermediate Trend Analysis) Method

The ITA method [29] was applied to analyze the internal structure of the minimum flow time series and identify successive phases of low water and relative recovery. Unlike classical approaches, ITA allows us to investigate local structural elements of the series based on the alternation of positive and negative anomalies, revealing its phase organization, degree of fragmentation, and stability. In the first stage, the time series is standardized (3):

$$Z_t = \frac{Q_t - \bar{Q}}{\sigma} \quad (3)$$

where Q_t is the minimum flow observation in year t; $\bar{Q}$ is the sample mean; and σ is the standard deviation, which allows the amplitudes of deviations to be compared independently of the absolute values of the flow. After standardization, the values are divided by sign, forming sequential sub-series:

$$Z_t \geq 0\text{—positive phases;}$$

$$Z_t \leq 0\text{—negative phases.}$$

A sequence is defined as a continuous sequence of observations of the same sign. For each sequence, the average value is calculated (4):

$$ITA_j = \frac{1}{n_j}\sum\nolimits_{t \in run_j} Z_t \quad (4)$$

which reflects the intensity of the corresponding phase. The resulting sequence of the ITA profile shows the alternation of structural blocks of increased and decreased flow and allows us to determine the stability of modes, transition periods, and the degree of internal non-stationarity.

In addition, three integral ITA indices are used:

The amplitude index $A = \overline{|ITA_j|}$ characterizes the severity of internal fluctuations (high values correspond to intense low-water or high-water phases).

The length index $L = \overline{n_j}$. determines structural stability (long sequences—stable regime; short sequences—fragmentation).

The isotropy index $I = 1 - \left| \overline{ITA^{+}} - |\overline{ITA^{-}}| \right|$

where

$\overline{ITA^{+}}$ is the average value of ITA for positive sequences; $\overline{ITA^{-}}$ is for negative sequences.

High isotropy reflects a symmetrical distribution of phases, while low isotropy reflects a predominance of low-water periods.

The advantage of ITA is its ability to reveal the hidden structure of a series that cannot be detected by break tests and linear trends. In conditions of high interannual variability of arid rivers, this method makes it possible to determine phases of sustained low water flow, recovery periods, and transitions associated with climate change.

Subsequently, ITA profiles are used to compare the internal structure of summer and winter runoff and are integrated with CSI_{min} and a modification of IPTA, which provides increased temporal detail (Figure 4).

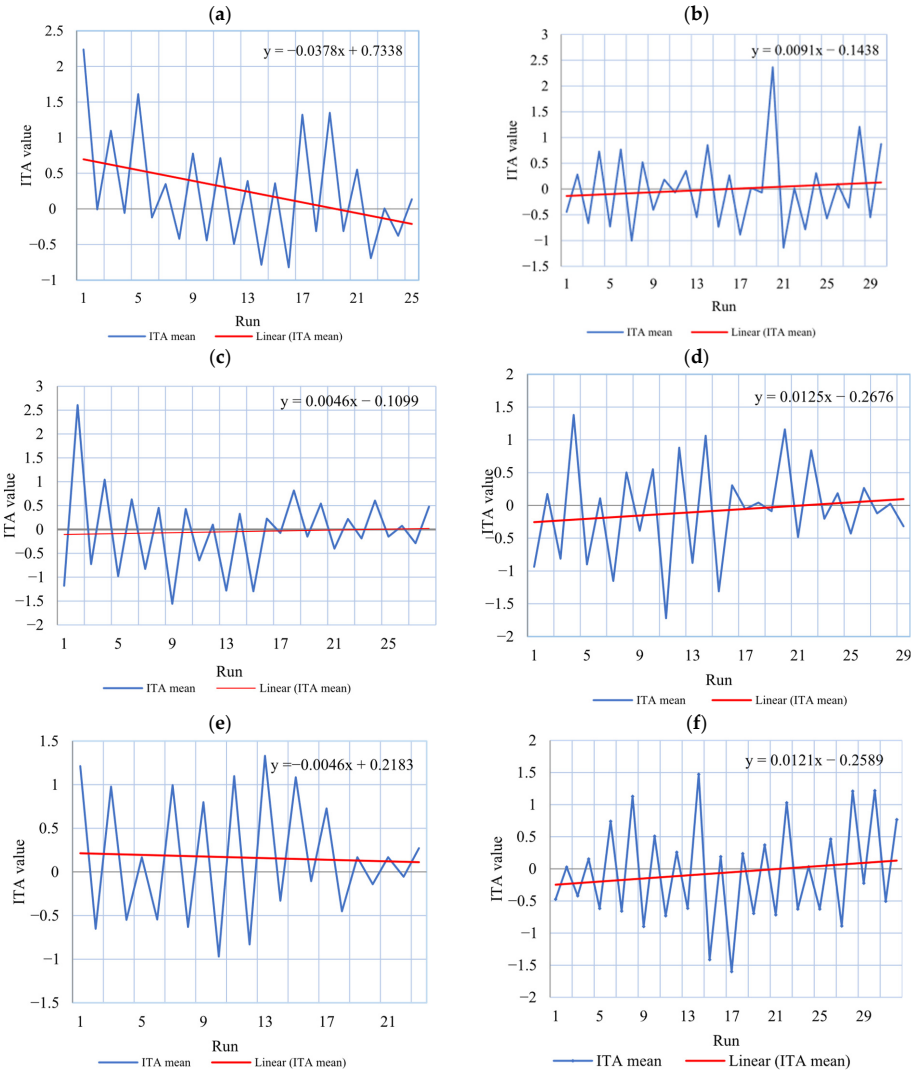

Figure 4. ITA profiles of minimum summer and winter runoff for the Temir, Oiyil, and Zhem rivers. (**a**) Temir, summer; (**b**) Temir, winter; (**c**) Oiyil, summer; (**d**) Oiyil, winter; (**e**) Zhem, summer; (**f**) Zhem, winter.

2.3.6. IPTA (Integrated Intermediate Trend Analysis) Method

The IPTA method is an integral modification of ITA and is used to detail the internal structure of minimum flow. Unlike ITA, based on the analysis of contracts of the same sign, IPTA allows you to track the continuous dynamics of anomalies and identify local

changes that are not recorded when averaging phases. As in ITA, the initial series is standardized (3), then an integral sequence is formed (5):

$$IPTA_t = \sum_{i=1}^{t} Z_i \quad (5)$$

which shows the accumulated deviation of the flow from the average state. The IPTA profile reflects the smooth evolution of internal phases and allows us to identify: transitions between periods of low water and recovery; sequential changes in the flow structure; local extremes consistent with climatic disturbances; and the interdecadal dynamics of climate control.

The advantage of the method lies in its ability to detect hidden structural features that are not apparent in the analysis of ITA sub-contracts. The integral form of the profile is sensitive to phase shifts, asymmetries, and accumulated anomalies, which is especially important for arid rivers, where minimum flow is formed under the influence of rare precipitation and high-frequency temperature fluctuations.

The use of IPTA in combination with the climate sensitivity index (CSI_{min}) allows us to compare the internal structure of runoff with the nature of climate control and determine the years of the most pronounced climate-induced changes.

The obtained IPTA profiles are used in subsequent sections to interpret structural changes, compare seasonal dynamics, and justify the mechanisms of minimum flow transformation under conditions of climatic non-stationarity (Figure 5).

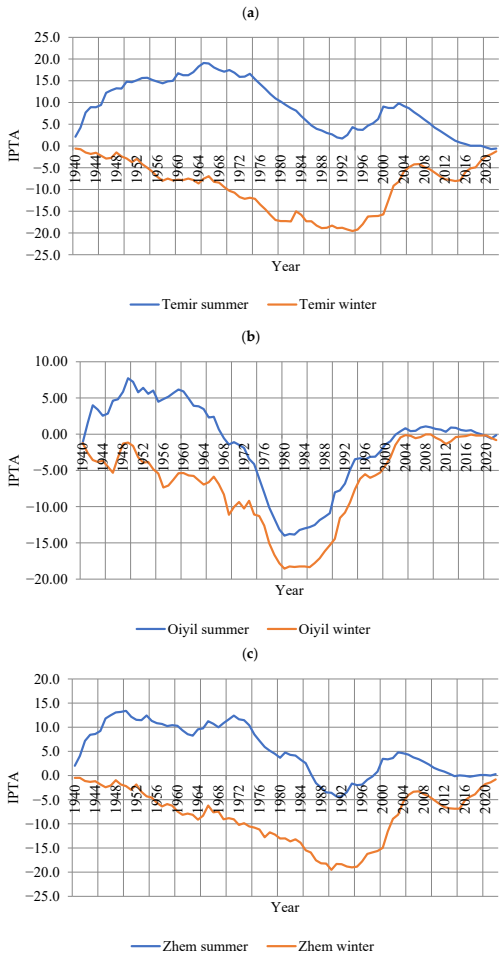

Figure 5. IPTA profiles of minimum summer and winter runoff for the (**a**) Temir, (**b**) Oiyil, and (**c**) Zhem rivers.

IPTA profiles are interpreted as integral phase polygons reflecting the trajectory of accumulated minimum flow anomalies and providing a continuous representation of the evolution of the hydrological regime.

2.3.7. Analysis of Intra-Row Structure Using the RAPS Method

The RAPS (Relative Accumulated Periodic Sums) method is a classic time series analysis tool widely used in hydrology, climatology, and geophysics to identify hidden anomalies, phase transitions, and prolonged periods of excess or deficit flow. Its key advantage is its ability to record cumulative deviations from the average level, forming an integral curve that visualizes the internal structure of the time series at different scales.

RAPS is constructed as the sequential sum of deviations of the value Q_t from the average value of the series (6):

$$\begin{gathered} R0 = 0 \\ R_t = \Sigma_i(Q_i - Q^-) \end{gathered} \quad (6)$$

The ascending part of the curve reflects periods of sustained high flow ($Q_i > Q^-$), while the descending part indicates prolonged phases of low flow ($Q_i < Q^-$). The amplitude, slope, and large-scale waves of the integral curve allow us to diagnose transitions of the hydrological system between different feeding regimes and to distinguish between climatically induced and internal structural changes.

Methodological stages of analysis:

The first stage of RAPS analysis is the standardization of the initial time series, which is expressed by Equation (7):

$$Z_t = (Q_t - Q^-)/\sigma \quad (7)$$

Then, the cumulative sum of deviations is calculated according to Equation (8):

$$R_t = \Sigma_i Z_i \quad (8)$$

The next step is to interpret the integral curve: a positive slope conveys a phase of increased runoff; a negative slope conveys a phase of sustained runoff deficit; inflection points convey a change in hydrological regime; and minimum or maximum points are potential moments of structural transformation.

The stage ends with a comparison of the results of the Pettitt test, the ITA/IPTA results, the trends, and the climate series for a comprehensive conclusion about the mechanisms of regime transformations.

The RAPS (Relative Accumulated Periodic Sums) method is used to identify the integral dynamics of minimum flow time series and complements the classical statistical tests and ITA/IPTA methods. Unlike point criteria (*t*-test, U-test, Pettitt), which record changes between subsamples, and ITA/IPTA, which analyze local phases and amplitudes, RAPS allows the cumulative effect of long-term deviations from the average flow level to be assessed. The integral RAPS curve reflects long periods of sequential decrease or increase in water content and its zero intersections mark the change in structural phases of the hydrological regime.

The method is particularly informative in conditions of climatic non-stationarity, as it reveals large-scale trends that are not always visible in linear trends or stationarity tests. The use of RAPS in combination with ITA/IPTA forms a representation of the internal structure of the series, enhancing the interpretation of the mechanisms of minimum flow formation and providing a more comprehensive analysis of hydrological changes.

A comparative overview of the methods used is presented in Table 4.

Table 4. Comparative analysis of scientific research methods.

Method of Analysis	Type	Purpose	Advantages
Pettitt Test	Nonparametric	Determination of the moment of structural break	Independent of distribution, robust to non-stationarity
Student's Criterion (*t*-Test)	Parametric	Comparison of mean values	High sensitivity under normality
Fisher's Criterion (F-Test)	Parametric	Comparison of variances	Effective in combination with the *t*-test
Mann–Whitney Test (U-Test)	Nonparametric	Comparison of medians	Not sensitive to distribution, resistant to outliers
ADF Test	Parametric	Stationarity test	Standard in hydroclimatology
Linear Trend	Parametric	Determination of the direction of change	Simple interpretation of long-term trends
Moving Average	Graphical	Smoothing and visual assessment	Clarity, no parametric restrictions
ITA (Intermediate Trend Analysis)	Transformational, structural	Analysis of positive/negative phases, amplitudes, length, and isotropy	Reveals hidden internal structure, resistant to non-stationarity
IPTA (Isotropic Phase Trend Analysis)	Structural	Integral phase dynamics, mode symmetry	Sensitive to sequential changes, detects structural skew
CSI (Climate Sensitivity Index of Minimum Flow)	Diagnostic	Assessment of the dominant climatic factor	Allows classification of climate control type and seasonal asymmetry
RAPS (Relative Accumulated Periodic Sums)	Integral, structural-dynamic	Identification of large-scale phases, prolonged periods of increased or decreased water content, as well as weak and prolonged changes in runoff levels	Allows assessment of intra-series consistency and stability; reveals hidden trends that are not captured by point tests; provides a comprehensive understanding of the time series structure.

The combination of methods provides a comprehensive analysis of minimum flow: from the diagnosis of structural breaks and trends to the assessment of stationarity, the internal organization of time series, and the determination of the prevailing climate control. This approach forms a holistic methodological basis for research and allows for reliable interpretation of seasonal and inter-basin differences in minimum flow under conditions of climatic non-stationarity.

3. Results

3.1. Minimum Summer Flow

The minimum summer flow of the Temir, Oiyil, and Zhem rivers demonstrates pronounced interannual variability, the presence of structural changes, directional trends, and signs of non-stationarity, which is especially characteristic of arid regions. A comparison of the results of the Pettitt test, homogeneity tests, the ADF test, the CSI_{min}, and the ITA/IPTA allowed us to link climatic influences with the characteristics of the internal phase organization of summer runoff.

3.1.1. Structural Shifts (Pettitt Criterion)

Analysis of minimum runoff using the Pettitt test criterion showed that both the summer and winter low-water periods of the Temir, Oiyil, and Zhem rivers underwent statistically significant structural shifts, confirming their pronounced non-stationarity and differences in climate sensitivity. Summer breaks (Temir—1967, Oiyil—1981, Zhem—1991) mark the transition to a regime with reduced water content and more frequent low-water phases, while winter shifts (Temir—1991, U = 911; Oiyil—1985, U = 883; Zhem—1989, U = 926; $p < 0.001$ for all rivers) reflect the restructuring of minimum winter flow and the transition to new phase states under conditions of changing cold-season moisture balance. A comparison of the two types of low flow shows that the summer phase responds mainly

through a prolonged decrease in water content, while the winter phase is characterized by more abrupt and synchronous phase transitions, which are particularly pronounced in the Zhem river basin. Taken together, this confirms the long-term climatic and hydrological restructuring of the minimum flow regime in the region.

3.1.2. Homogeneity of Time Series (*t*-, F-, U-, and Wilcoxon Tests)

A comprehensive assessment of the homogeneity of the minimum flow time series, performed using parametric (*t*-tests, F-tests) and nonparametric (Wilcoxon and Mann–Whitney criteria) methods (Table 5), showed that in the Temir, Oiyil, and Zhem, the previously identified structural breaks are accompanied by statistically significant changes in the central characteristics of both summer and winter low water flow ($p < 0.05$). This indicates a transition of the studied watercourses to a new level of minimum flow and confirms a violation of the temporal homogeneity of the hydrological series. Summer minimum flow is characterized by a predominant shift in the average level while maintaining dispersion properties in the Oiyil and Zhem river basins, which indicates a change in the base level of the low-water period with an unchanged amplitude of interannual variation. In the case of the Temir river, changes in both the mean and dispersion are recorded, reflecting a more profound restructuring of the regime and confirming the increased climatic sensitivity of this basin. Analysis of the winter minimum flow shows a similar trend, but the structural changes are much more pronounced. For the Temir and Zhem rivers, all the criteria used record a statistically significant change in central tendencies and distributions in the absence of reliable differences in variances, which corresponds to the typical configuration of a climate-driven shift in flow levels while maintaining internal variability. The Oiyil River basin occupies an intermediate position: with a statistically significant change in means and distributions, the F-test value ($p = 0.0519$) indicates a borderline nature of changes in the dispersion structure.

Table 5. Results of the analysis of the homogeneity of minimum flow time series of the Temir, Oiyil, and Zhem rivers.

Water Body	Season	Student's *t*-Test (for Difference in Means)	Fisher's F-Test (for Differences in Variances)	Wilcoxon Signed-Rank Test (Nonparametric Test)	Mann–Whitney U-Test (Test for Differences Between Samples Based on Rank Characteristics)
Temir River	Summer	0.000031	0.0354	0.0000013	0.0000054
	Winter	0.00018	0.9998	0.00075	0.00030
Oiyil River	Summer	0.00197	0.998	0.00021	0.00059
	Winter	0.0023	0.0519	0.0027	0.0015
Zhem River	Summer	0.039	1.54	0.048	0.021
	Winter	0.0060	0.994	0.013	0.0071

Overall, the results (Table 5) demonstrate a consistent change in the minimum flow level during the warm and cold seasons, with the winter low-water period characterized by a more pronounced and uniform response between basins, while the summer period reveals significantly different types of response, especially in the case of the Temir river. The data obtained confirm the violation of the temporal uniformity of hydrological series and record the transition of the studied river systems to new climatic and hydrological regimes of minimum flow formation.

3.1.3. Long-Term Trends and Moving Trends

A synthesis of long-term trends and sliding trends in minimum flow shows that the seasonal structure of low water levels in all of the studied river systems is formed under the influence of stable climatic and hydrological changes, but the nature of the flow response in the warm and cold seasons differs significantly. A combined analysis of summer and winter

series reveals a complex but regular dynamic in which both seasons form complementary components of a single minimum flow regime.

Summer minimum runoff generally demonstrates a more pronounced sensitivity to long-term climate change: moving trends show a gradual decrease in water content, accompanied by a smoothing of interannual variability and a lengthening of negative phases. This dynamic reflects the accumulation of the climate signal in conditions of increased dependence of summer interannual variation on atmospheric aridity, precipitation deficit, and changes in the evaporation balance. The trends formed during the warm season are characterized by directionality and stability, which determines the leading role of the summer period in the overall restructuring of minimum flow.

Winter minimum flow, on the contrary, has higher structural stability and exhibits less-pronounced trend components. Moving averages indicate a smoothed nature of seasonal changes and the absence of a long-term drift for most observations. However, winter dynamics record individual phase shifts, which represent the system's response to changes in the cold-season water balance, including changes in snow accumulation patterns, ice processes, and winter precipitation. At the same time, winter runoff reacts more sharply but briefly, demonstrating distinct structural transitions with a smaller overall trend toward long-term decline (Figure 6).

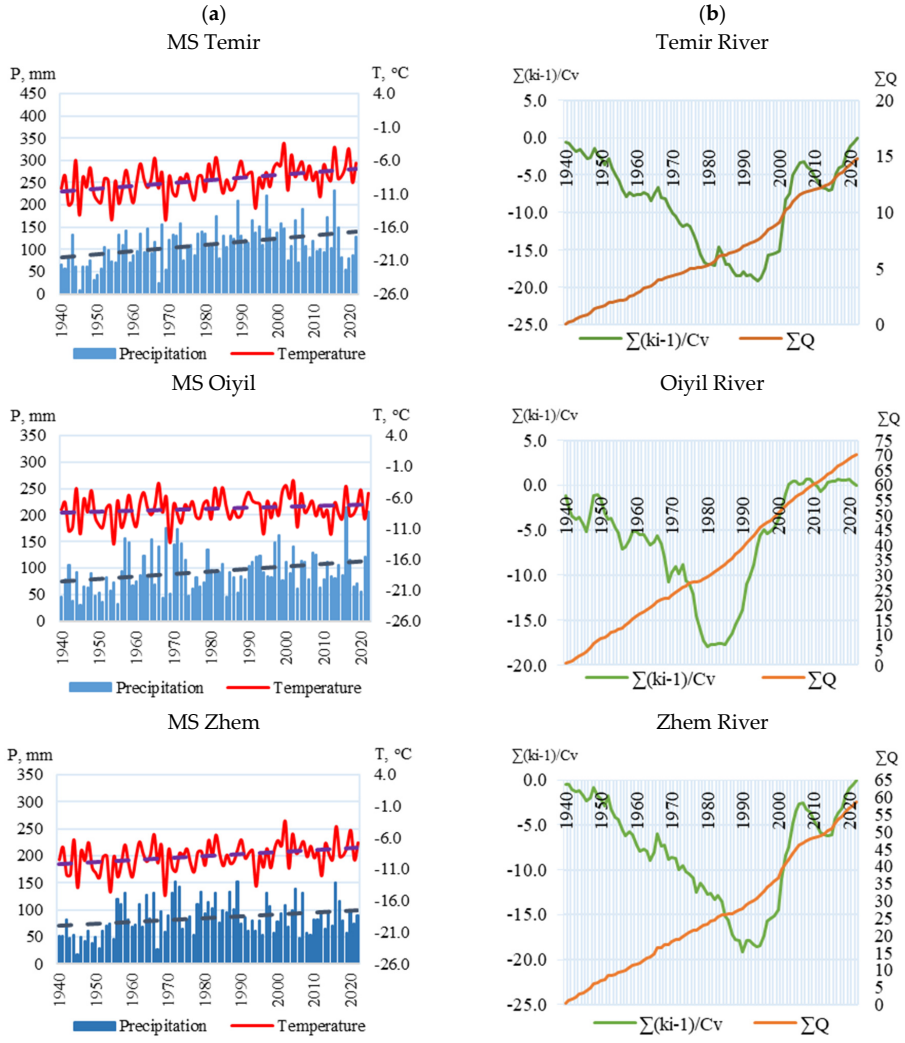

Figure 6. Dynamics of changes in hydrometeorological parameters in the basin under consideration of: (**a**) atmospheric precipitation and air temperature during the winter season; (**b**) differential integral and total curves of minimum winter flow.

A comparison of seasonal components reveals a key pattern: the summer low-water period forms the main trend of long-term reduction in minimum flow, while the winter low-water period determines its structural stability, acting as a stabilizing element of the annual regime. The interaction of these two components leads to a complex spatial–temporal configuration of low water levels, in which the summer trend drift is intertwined with winter phase variability. Taken together, the results indicate the formation of a stable trend in the region towards a decrease in minimum flow during the warm season, while maintaining relative stability in winter minimum flows, disrupted only by isolated structural changes. Such a seasonally differentiated response of hydrological systems emphasizes the decisive role of the climatic factor and justifies the need for a comprehensive analysis combining trend characteristics and the internal structure of time series.

3.1.4. Stationarity of Time Series (ADF Test)

The stationarity of minimum flow time series was assessed using the Augmented Dickey–Fuller (ADF) test, which allows the diagnosis of the presence of a unit root and determination of the nature of the long-term dynamics of hydrological processes. The results obtained (Table 3) indicate pronounced inter-basin heterogeneity for both the summer and winter periods.

The results of the ADF test show that the summer minimum flow series are, in most cases, characterized by non-stationarity, reflecting the influence of long-term climatic trends and structural changes in river flow.

For the Temir River, the ADF statistic -2.34 ($p = 0.16$) confirms pronounced non-stationarity, which is consistent with the established steady decline in summer Q_{min} and the prolonged negative phase of the 1970s–1990s.

The Oiyil river (ADF = -2.73; $p = 0.06$) occupies an intermediate position: formally, the null hypothesis is not rejected, but the proximity of the p-value to the critical level reflects the smoothed nature of the variations and the partial stability of the internal structure.

In contrast, the Zhem river demonstrates confident stationarity (ADF = -5.19; $p \ll 0.001$). Despite individual periods of reduced Q_{min} values, the dynamics of the series are described by fluctuations around a stable average without a sustained trend.

The assessment of the winter time series revealed other characteristic features of the dynamics. For the Temir river, the winter minimum flow is strictly stationary (ADF = -5.36; $p = 0.000004$). A significant excess of the critical level indicates the absence of a single root and the high structural stability of the series. This result is consistent with the pronounced smoothness of winter dynamics and the absence of trend drift after the climatic break.

The Oiyil river shows signs of non-stationarity (ADF = -2.41; $p = 0.14$), indicating the presence of long-term drift, structural heterogeneity, or ongoing restructuring of the winter hydrological regime. This confirms the need for an in-depth structural analysis, presented in the following sections.

For the Zhem river, the winter series is characterized by borderline stationarity (ADF = -2.88; $p = 0.047$). Despite formal confirmation of stationarity, the proximity of ADF statistics to the critical threshold indicates the possible influence of weak trend or structural components consistent with the phase transitions identified by the Pettitt method.

3.1.5. Climatic Typology of Minimum Flow (CSI_{min})

To identify the mechanisms of climatic control of minimum flow and determine the differences in the hydrological sensitivity of river systems, a typology of Qmin climatic control regimes was developed. The approach is based on the correlation between minimum flow and two key climatic drivers—air temperature (T) and precipitation (P)—which

allows river sections to be classified (Table 6) according to the dominant climatic factor and their degree of climatic sensitivity to be quantified.

Table 6. Classification of climatic control modes of minimum runoff (typology I–IV).

Type	Condition	Description
Type I—temperature-controlled regime	r(T) > 0.5 and r(P) < 0.3	Minimum flow is controlled mainly by air temperature. An increase in temperature increases evaporation, reduces replenishment, and decreases Q_{min}.
Type II—moisture-dependent regime	r(P) > 0.5 and r(T) < 0.3	Precipitation (rainfall/snow accumulation) becomes the main determining factor for Q_{min} during periods when temperature control is weak.
Type III—mixed regime	r(T) > 0.4 and r(P) > 0.4	Both factors—temperature and precipitation—significantly influence Q_{min}, creating a balanced response.
Type IV—inert mode	r(T), r(P) < 0.3	Climatic factors have a weak influence on Q_{min}. Runoff dynamics may be determined by other factors.

The introduced typology includes four classes of regimes (types I–IV), differing in the degree of influence of temperature and humidity, including temperature-controlled (type I), moisture-dependent (type II), mixed (type III), and inert (Type IV), in which the climatic impact is weak. This scheme provides a systematic description of the mechanisms of minimum runoff formation under conditions of general aridization and high interannual climate variability in Western Kazakhstan.

The classification results (Table 7) demonstrate clear seasonal differentiation in climatic control. In the summer period, temperature control is the dominant driver for most rivers: negative correlations between Qmin and temperature reflect increased evaporation losses and reduced effective moisture. The exception is the summer regime of Temir, which functions as a mixed system, where the contribution of precipitation is comparable to the temperature effect. The least climatic dependence of the summer dry season was observed in Oiyil, for which an inert regime was identified, indicating the dominance of non-climatic factors (geomorphology, local underground runoff).

Table 7. Typology of Q_{min} climate control regimes for the Temir, Oiyil, and Zhem rivers.

River—Station	Season	r(Q_{min}, T)	r(Q_{min}, P)	Mode Type	Dominant Factor
Temir—Lensky	Summer	−0.356	0.385	Type III	Mixed
	Winter	0.690	0.314	Type I	Temperature
Oiyil—Taltogay	Summer	−0.215	0.262	Type IV	Inert
	Winter	0.372	0.212	Type I	Temperature
Zhem—Zharkamys	Summer	−0.464	0.153	Type I	Temperature
	Winter	0.571	0.199	Type I	Temperature

The winter period is characterized by a noticeable increase in temperature control. For all rivers, except for the winter regime of Oiyil, a temperature-controlled type (type I) has been identified, which is consistent with the continuous increase in winter temperatures and a decrease in the depth of soil profile freezing. Oiyil, on the contrary, is characterized by a moisture-driven regime, reflecting the important role of winter precipitation and snow accumulation processes in the formation of Qmin, with a relatively weak thermal influence.

To quantitatively assess the seasonal differences in the influence of temperature and precipitation, the climatic sensitivity index of minimum runoff CSI_{min} (Table 8) was calculated, which allows the determination of the dominant factor controlling runoff in a generalized form.

Table 8. Climate sensitivity index of minimum runoff and type of climate control.

River—Station	Season	$r(Q_{min},T)$	$r(Q_{min},P)$	CSI_{min}	Control Type
Temir—Lensky	Summer	−0.356	0.384	−0.519	Intermediate (sedimentary control predominates)
	Winter	0.610	0.314	+0.319	Intermediate (temperature-dominated)
Oiyil—Taltogai	Summer	0.372	0.381	−0.012	Intermediate (balanced)
	Winter	−0.215	0.333	−0.558	Intermediate (sediment-controlled)
Zhem—Zharkamys	Summer	−0.305	0.390	−0.533	Intermediate (sediment-controlled)
	Winter	0.585	0.335	+0.272	Intermediate (temperature prevails)

The index values confirm that summer minimum flow depends mainly on moisture, with precipitation having a stronger influence than temperature on the Zhem and Temir rivers. Winter minimum flow is generally controlled by temperature, which is consistent with general warming trends and the results of the ADF test and Pettitt analysis. Oiyil exhibits the most balanced and low-contrast response, confirming its intermediate nature of climate control.

Analysis of the CSI_{min} values and climate control structures suggests that the minimum flow of the studied rivers functions as a system with complex, seasonally differentiated climate control. In summer, moisture availability plays a key role, while in winter, temperature regime and frost depth are important. This climatic typology reflects the characteristics of the hydrological response of river systems in arid zones and is an important tool for predicting future changes in low-water conditions in the context of continuing warming and increasing climatic instability.

3.1.6. ITA Profiles (Internal Structural Organization)

Analysis of the ITA profiles revealed a clear seasonal differentiation and significant spatial variability in the internal structure of minimum flow (Table 9). Summer series are characterized by a predominance of negative sequences, reflecting the stability of low-water phases and the high fragmentation of temporal structures. Short sub-series (on average 2.96–3.61 years) and their frequent replacement indicate the high-frequency reactivity of summer runoff to interannual climatic fluctuations, which is typical for arid catchments with episodic moistening. High values of the summer ITA amplitude, especially pronounced in the Temir basin, confirm its increased sensitivity to climatic influences. In contrast, the minimum amplitude and rarity of large phase deviations characteristic of the Zhem river indicate a more stable internal structure of the summer intermonsoon period.

Table 9. ITA characteristics of the internal structure of the minimum flow of the Temir, Oiyil, and Zhem rivers.

River/Season	Average Length of the Contract	Maximum Length of the Contract	Average ITA Amplitude	Maximum ITA Amplitude	Isotropy Index	Heterogeneity Index and (Number of Contracts)
Oiyil, summer	2.96	13	0.654	2.606	−0.480	28
Oiyil, winter	2.86	11	0.596	1.722	−0.523	29
Temir, summer	3.32	18	0.630	2.238	−0.589	25
Temir, winter	2.77	13	0.594	2.365	−0.530	30
Zhem, summer	3.61	11	0.621	1.331	−0.574	23
Zhem, winter	2.59	13	0.672	1.600	−0.561	32

It should be emphasized that the analysis of the ITA profiles was performed in strict accordance with the methodological requirements of innovative trend analysis, which

assume the comparability of time subperiods, equal length of the analyzed segments, and interpretation of the results not by the average trend, but by the internal phase structure of the series. In this study, ITA was used not as an indicator of the presence or absence of a trend as a whole, but as a tool for diagnosing the internal organization of a time series, allowing for a quantitative characterization of the length, direction, and amplitude of successive phases of minimum flow.

The ITA indicators used (the average and maximum length of contracts, amplitude of phase deviations, and isotropy and heterogeneity indices) are considered in the paper as formalized characteristics of the stability and directionality of the phase structure of minimum flow. Their joint analysis allows us to assess the degree of fragmentation of the time series, the dominance of degradation or recovery phases, and to identify seasons and basins with increased structural instability, which corresponds to the basic tasks of ITA in the analysis of non-stationary hydrological series.

Negative values of the isotropy index ($-0.480 \ldots -0.589$) confirm the pronounced orientation of the summer phases, which are dominated by low-water conditions. The number of summer sub-series (23–28) indicates a highly fragmented series structure, which is consistent with the episodic nature of summer hydrological recharge.

Winter ITA profiles demonstrate a fundamentally different structural organization. With similar average sequence lengths (2.59–2.86 years), winter series are less fragmented, which is reflected in an increased number of sequences (29–32) and a more symmetrical alternation of positive and negative phases. This behavior reflects the stability of the winter regime, which is determined by low-frequency processes of underground recharge and moisture accumulation during the cold period. The amplitudes of winter ITA fluctuations (0.59–0.67 on average and 1.60–2.36 at maximum) are lower than in summer, which confirms the smoothed nature of winter dynamics and the lesser severity of extreme deviations.

The maximum duration of phases (11–18 years in summer and 11–13 years in winter) emphasizes the presence of long-term stable conditions in both seasons, but summer extremes are characterized by greater amplitude and more abrupt transitions between phases. The most pronounced structural anomalies (1941–1946) are recorded synchronously in all basins, indicating the regional nature of the climatic impact.

The combination of ITA characteristics quantitatively confirms the pronounced seasonal asymmetry of the internal structure of minimum flow: summer demonstrates a high-frequency, fragmented, and thermosensitive regime, while winter is characterized by a more stable, smoothed, and low-frequency organization. These differences are consistent with the results of the analysis of stationarity, structural shifts, and climatic typology of Qmin and serve as the basis for subsequent IPTA of the phase evolution of structural changes.

3.1.7. IPTA Profiles (Phase Symmetry and Structural Stability)

The analysis of the IPTA profiles is based on the construction of innovative polygons (IPTA polygons) formed in the space of ordered values of minimum flow for comparable sub-periods of the time series. Unlike the discrete ITA approach, which focuses on the analysis of individual phase segments, the IPTA polygon reflects the continuous integral evolution of minimum flow deviations, allowing for visual and analytical assessment of phase symmetry, stability, and the directionality of accumulated changes. In this study, IPTA is applied in its full methodological form, where the polygon acts as a key diagnostic element in the analysis of the structural restructuring of the minimum flow regime (Figure 5).

The geometry of IPTA polygons allows us to interpret not only the sign and magnitude of integral deviations, but also the nature of the structural evolution of the hydrological

system. The broken shape of the polygon and the presence of inflections indicate phase-heterogeneous, impulsive dynamics, while smoothed and monotonic sections reflect the formation of a stable integral regime. In this sense, the IPTA polygon is a tool for identifying transitions of the hydrological system between different structural states, which is fundamentally impossible when using exclusively local or parametric methods.

Analysis of the temporal dynamics of the IPTA profiles shows that after the 1980s, there was a marked decrease in the amplitude of fluctuations and an increase in the structural orderliness of minimum flow. This is manifested in a decrease in phase contrast, smoothing of integral curves, and the formation of more stable regimes, which are especially pronounced in the winter period. This transformation reflects the transition from the high-amplitude, climatically unstable structure of the mid-20th century to the more inertial and low-frequency dynamics of the end of the time series.

Summer IPTA profiles are characterized by high variability and a pronounced broken shape, which indicates the absence of a stable integral regime and the dominance of short-lived climatically induced anomalies. Frequent changes in the direction of accumulated deviations reflect the reactive nature of summer minimum runoff, formed under conditions of episodic moistening, high evaporation, and sensitivity to extreme temperature and precipitation impulses. In the post-1980s, the summer regime is gradually transforming into shorter and more fragmented phases, which is typical for systems with high climatic sensitivity.

For the Temir and Oiyil river basins, summer IPTA curves show sharp local inflection points consistent with periods of extreme low-water episodes. In the Temir river, the most contrasting amplitudes and large phase blocks are recorded in the 1940s–1960s period, while in the second half of the series, prolonged periods of sustained low water levels are formed. The Oiyil river is characterized by more pronounced fragmentation and short phases (2–3 years), indicating its high responsiveness to short-term climatic impulses. The Zhem river is characterized by the most smoothed and inertial structure of summer IPTA profiles with directed downward integral dynamics, reflecting a stable sedimentary dependence of minimum flow.

Winter IPTA profiles differ fundamentally in form and dynamics. For all rivers studied, the winter period is characterized by smoother and more monotonous integral curves, elongated phase sequences (up to 11–13 years), moderate amplitudes, and high phase symmetry. This structure indicates the dominant role of underground recharge and low-frequency processes associated with the regional temperature signal, a decrease in the depth of freezing, and an increase in infiltration recharge. The most pronounced upward integral dynamics of winter minimum flow is recorded for the Temir and Zhem rivers, which is consistent with the temperature-type climate control identified by the CSI_{min}.

In general, IPTA profiles confirm the predominance of negative phases of minimum flow in the mid-20th century, a significant weakening of the amplitude after the 1980s, the synchronism of key structural changes, and the gradual stabilization of the internal structure of minimum flow. At the same time, there is a pronounced shift towards low-water conditions, especially in the summer period, which is consistent with the results of trend analysis and homogeneity tests.

A comparison of IPTA profiles with the results of ITA and RAPS analysis demonstrates their high consistency. Periods of sharp fragmentation of ITA sub-contracts and changes in phase structure coincide with inflection points in IPTA curves and extremes in RAPS profiles, confirming the systematic rather than random nature of the changes identified. The integral nature of IPTA allows us to identify key intervals of phase transitions that coincide with structural breaks established according to the Pettitt criterion and changes in climatic parameters.

Together, ITA, IPTA, and RAPS form a multi-level system for analyzing the internal structure of minimum flow, in which ITA is used to diagnose the discrete phase organization of the time series, IPTA is used to analyze the integral evolution of phases and structural stability, and RAPS records the accumulation of anomalies over time. This approach provides a comprehensive picture of the climate-driven evolution of the minimum flow of arid rivers in Western Kazakhstan and allows for a quantitative description of the degree of seasonal asymmetry, stability, and inter-basin differentiation of hydrological regimes.

3.1.8. Integral Dynamics of Minimum Flow (RAPS Method)

To conduct an in-depth assessment of the long-term evolution of minimum flow and identify stable phases of the hydrological regime, the Rescaled Adjusted Partial Sums (RAPS) method was applied. Unlike local and rank methods (ITA, IPTA), which are primarily focused on identifying trend direction and distribution anisotropy, RAPS allows for the analysis of the integral behavior of a time series, recording prolonged periods of dominance of positive or negative deviations from the mean.

Figure 7 shows the integral RAPS curves for the minimum summer and winter flows of the Oiyil, Temir, and Emba rivers. Each curve reflects the cumulative effect of hydrological anomalies, which allows changes to be interpreted not as isolated events, but as phase states of water content that change over time.

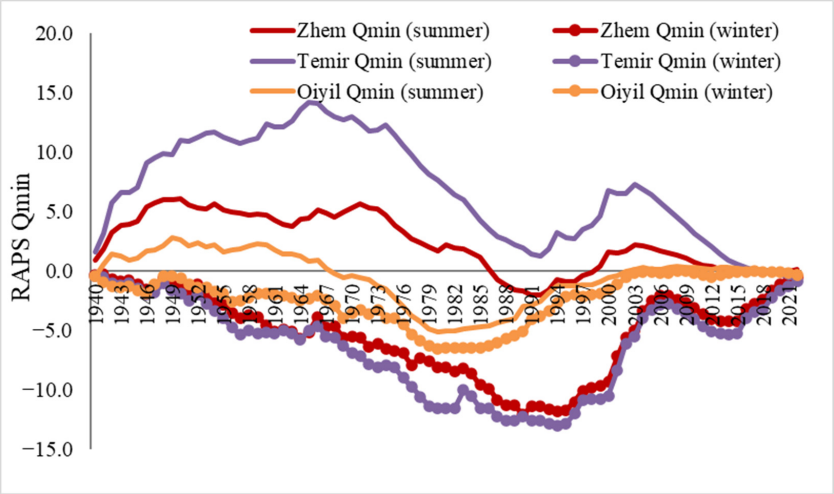

Figure 7. Graphic representation of RAPS for the series of minimum summer and winter runoff for the Zhem, Temir, and Oiyil rivers.

Analysis of RAPS curves revealed a clearly defined phase structure for all rivers studied, consistent with the results of the Pettitt test and IPTA. Summer minimum flow is characterized by extended downward sections of integral curves in the period from the 1940s to the 1960s, indicating a prolonged phase of reduced water availability. This period apparently reflects regional climate aridization and a decline in the role of base flow amid reduced summer precipitation.

In the 1970s–1980s, most curves show turning points (inflection points), after which the nature of the accumulation of deviations changes. These moments are consistent with the established points of structural breaks (1967–1991 for the summer period), confirming that the identified breaks represent boundaries between different phases of the hydrological regime, rather than random statistical fluctuations.

For winter minimum flow, the integral curves show different dynamics. After a pronounced downward phase until the early to mid-1980s, there is a steady upward segment of the RAPS curves, which is particularly pronounced after the 1990s. This indicates a systematic increase in low-flow discharge, which is consistent with rising air

temperatures, a reduction in the depth of seasonal freezing, and an increase in the role of underground river feeding during the cold season. Thus, RAPS confirms a climate-driven transition to more stable winter discharge conditions.

A comparative analysis of rivers shows differences in the nature of integral dynamics. The Temir river is characterized by the most contrasting phase structure: pronounced downward segments in the mid-20th century are replaced by a steady increase in minimum flow in the post-Soviet period, which corresponds to the identified winter trend and high temperature sensitivity of the basin. The Oiyil river is characterized by prolonged periods of negative accumulated deviations, especially in the summer, which confirms the ITA/IPTA results on the high fragmentation and instability of the summer regime. The Zhem river shows a smoother shape in its RAPS curves, but distinct deviations in the 1970s–1990s indicate its sensitivity to interannual precipitation variability and arid conditions. An important result of applying the RAPS method is the identification of the inertial and cumulative nature of changes in minimum flow. The structural shifts identified by Pettitt and IPTA are in fact a reflection of transitions between long-term phases of water availability formed under the influence of climatic factors on a multi-year scale. However, interpreting changes in minimum flow based solely on local or distributional methods (ITA, IPTA) remains incomplete without taking into account the integral temporal structure of the series. The application of the RAPS method has shown that the identified trends and anisotropies are not isolated statistical features, but elements of a larger-scale phase evolution of the hydrological regime. Integral RAPS curves made it possible to identify stable multi-year periods of reduced and increased minimum water content, within which local changes recorded by ITA/IPTA acquire a physically meaningful context.

In this sense, RAPS is not an auxiliary, but a structuring tool of analysis, linking the results of breakpoint and directionality tests into a unified concept of phase non-stationarity of minimum flow. Breaks in RAPS curves, coinciding with points of structural breaks (according to Pettitt), confirm that changes in minimum flow are caused by transitions between different climatic and hydrological regimes, rather than random interannual variability. The ITA and IPTA methods refine the nature of changes within phases, while RAPS sets the boundaries and duration of the phases themselves, providing a comprehensive interpretation of the non-stationarity of minimum flow on a multi-decadal time scale. The RAPS method provides a comprehensive picture of the phase-integral evolution of minimum flow and complements the results of ITA and IPTA. The combined use of ITA, IPTA, and RAPS polygons made it possible to move from point diagnostics of changes to a systematic analysis of long-term dynamics, eliminating the fragmentary nature of time series interpretation and significantly enhancing the reliability of conclusions about the non-stationarity of the hydrological regime of the rivers under study.

3.2. Climatic Parameters

The analysis of climatic conditions for the formation of minimum flow in the Temir, Oiyil, and Zhem river basins was performed using long-term series of air temperature and atmospheric precipitation for 1940–2022. Particular attention was paid to long-term trends, interannual variability, and the phase structure of climatic parameters, which allows for a comparison of the climatic background with gaps, trends, and the internal structure of minimum flow.

3.2.1. Structural Changes in Climatic Parameters

To identify possible climatic shifts, the Pettitt test was used to determine the moments of structural breaks in seasonal series of air temperature and atmospheric precipitation. The results obtained for the Temir, Oiyil, and Zhem rivers are presented in Table 10 and

demonstrate marked differences in the dynamics of climatic parameters. For summer temperatures, significant breaks were identified at the Temir MS (1995) and Zhem MS (1975), reflecting a steady increase in the temperature background during the warm season; no statistically significant change was found at the Oiyil MS. In the winter season, structural changes in the temperature regime were confirmed for the Temir (1980) and Zhem (1977) rivers, while for the Oiyil river (1961), the existence of a gap was not confirmed at the required level of significance.

Table 10. Structural changes in seasonal air temperatures and atmospheric precipitation in the basins of the rivers under study (Pettitt test).

Parameter	Period	Weather Station	Year of Break (Pettitt)	Statistics	*p*-Value	Conclusion
T, °C	Summer	Temir	1995	1086.0	0.00014	There has been a systemic change in the median summer temperature.
		Oiyil	1981	438.0	0.398	No evidence of structural shift
		Zhem	1975	1328.0	0.00001	Statistically significant warming during the summer period has been recorded
	Winter	Temir	1980	1032.0	0.00026	The *p*-value indicates high statistical significance
		Oiyil	1961	556.0	0.148	The statistical significance of this shift has not been confirmed.
		Zhem	1977	753.0	0.014	The p-level value is significantly lower than the significance level, which indicates the presence of a statistically significant shift.
P, mm	Summer	Temir	2007	492.0	0.279	The p-level value is significantly higher than the significance level, which means that the hypothesis of a structural gap is rejected.
		Oiyil	1944	407.0	0.519	The p-level value exceeds the standard significance level of 0.05, indicating that there is no statistically significant structural shift.
		Zhem	2006	384.0	0.434	The hypothesis of a break is not confirmed—the series retains its structural integrity.
	Zima	Temir	1970	1197	0	A low *p*-value indicates a high degree of reliability of the change
		Oiyil	1955	989.0	0.00053	The significance level is significantly lower than the threshold value, which allows us to state with a high degree of confidence that there has been a one-time change in the distribution of precipitation in the winter period.
		Zhem	1970	1178	0.00002	The low *p*-value indicates a high degree of certainty that there has been a break in the distribution of winter precipitation.

The seasonal dynamics of atmospheric precipitation are characterized by a different structure. Summer precipitation at all three stations (Temir, Oiyil, Zhem) does not show statistically significant shifts, which indicates the absence of long-term changes in the summer moisture regime and emphasizes the role of episodic interannual variability. In contrast to the summer period, winter precipitation is characterized by clearly pronounced structural changes: breaks were recorded at the Temir and Zhem stations in 1970 and at the Oiyil station in 1955. These changes coincide in time with transitions in winter minimum flow, which indicates a possible climatic cause for changes in the winter hydrological regime.

A summary analysis of climatic breaks shows that air temperature exhibits the most stable and pronounced structural changes, manifested both in summer and especially in winter. This indicates a transition of the regional climate system to a new temperature regime, which is consistent with the established transformation of winter minimum flow. Summer precipitation does not show statistically significant shifts, which emphasizes the episodic nature of its influence on the formation of summer Qmin and the absence of a

long-term systemic trend in summer moisture. At the same time, winter precipitation shows synchronous structural breaks in the 1955–1970 interval, coinciding in time with the phases of subsequent growth in winter minimum runoff. This consistency confirms the key role of winter moisture and related mechanisms of underground and infiltration feeding in the formation of winter Qmin.

Analysis of the data obtained shows that the temperature regime is the key driver of climatic structural changes in the region.

In the summer period, significant breaks are recorded at the Temir (1995) and Zhem (1975) stations, which is consistent with the intensification of summer warming at the end of the 20th century. No structural shift has been established at Oiyil, reflecting a more gradual change in summer temperatures.

In the winter season, climatic breaks have been confirmed at Temir (1980) and Zhem (1977), indicating a transition to a stable phase of winter warming. For the Oiyil station, the 1961 break has not been statistically confirmed.

The picture for precipitation is the opposite: summer precipitation remains structurally homogeneous at all stations; winter precipitation shows synchronous breaks (Temir—1970, Oiyil—1955, Zhem—1970), indicating a regionally coordinated restructuring of winter moisture.

The identified climatic breaks are consistent with hydrological patterns, namely: a steady increase in winter minimum runoff (Section 3.2); phase shifts in winter ITA/IPTA profiles; positive values of CSI_{min} for the winter period; the formation of a prolonged positive climatic phase after 1970–1980.

Thus, climatic structural shifts serve as the fundamental basis for the restructuring of winter minimum flow, while their influence is significantly weaker in the summer season.

3.2.2. Homogeneity of Climatic Parameters

The homogeneity of seasonal precipitation series was analyzed using the *t*-test, F-test, and Mann–Whitney U-test (Table 11), which revealed clear differences between summer and winter moisture regimes. At the Temir weather station, the summer series is characterized by complete homogeneity across all criteria ($p > 0.27$), indicating the absence of any structural changes, while the winter season shows statistically significant changes in mean values and distributions (*t*-test $p = 0.00002$; U-test $p < 0.0001$) while maintaining stable dispersion, which indicates a restructuring of the winter moisture regime. A similar seasonal contrast is observed at the Oiyil weather station: the summer series is homogeneous ($p > 0.31$), while the winter period is characterized by moderate heterogeneity, manifested in statistically significant differences in means and distributions (*t*-test $p = 0.024$; U-test $p = 0.0066$), reflecting a gradual change in winter moisture conditions. At the Zhem weather station, the summer regime also remains homogeneous ($p > 0.07$), confirming the absence of long-term changes in summer precipitation, while the winter series shows pronounced changes in mean values and distributions with stable dispersion (*t*-test $p = 0.00003$; U-test $p < 0.0001$), indicating a significant shift in the winter regime of atmospheric precipitation.

Summer precipitation at all stations retains structural homogeneity, confirming the absence of long-term climatic changes during the warm season. Winter precipitation shows regionally consistent heterogeneity (Temir, Oiyil, Zhem) associated with changes in the nature of the cold season. The heterogeneity of winter precipitation is consistent with: identified breaks [22], an increase in winter minimum runoff (Section 3.2), intensified winter warming, and changes in infiltration processes.

Thus, precipitation variability has a pronounced seasonal asymmetry: the summer regime remains stable, while the winter regime has undergone significant climatic changes.

Table 11. Assessment of the homogeneity of summer precipitation series in the Temir, Oiyil, and Zhem river basins.

MS	Period	*t*-Test (*p*)	F-Test (*p*)	U-Test (*p*)	Conclusion
Temir	Summer	0.722	0.278	0.534	Homogeneous series, no statistically significant differences identified
	Winter	0.00002	0.999	<0.0001	Significant change in average level with stable dispersion
Oiyil	Summer	0.486	0.514	0.317	Homogeneous rows without signs of shift
	Winter	0.024	0.976	0.006	Moderate heterogeneity of average level with stable dispersion
Zhem	Summer	0.875	0.074	0.673	Homogeneous series, no statistical differences identified
	Winter	0.00003	0.999	<0.0001	Significant violation of the homogeneity of the average level

3.2.3. Long-Term Changes in Air Temperature

Analysis of long-term air temperature has revealed a steady and statistically significant warming in both the summer and winter seasons, but the nature of the changes shows a pronounced seasonal asymmetry (Figure 8).

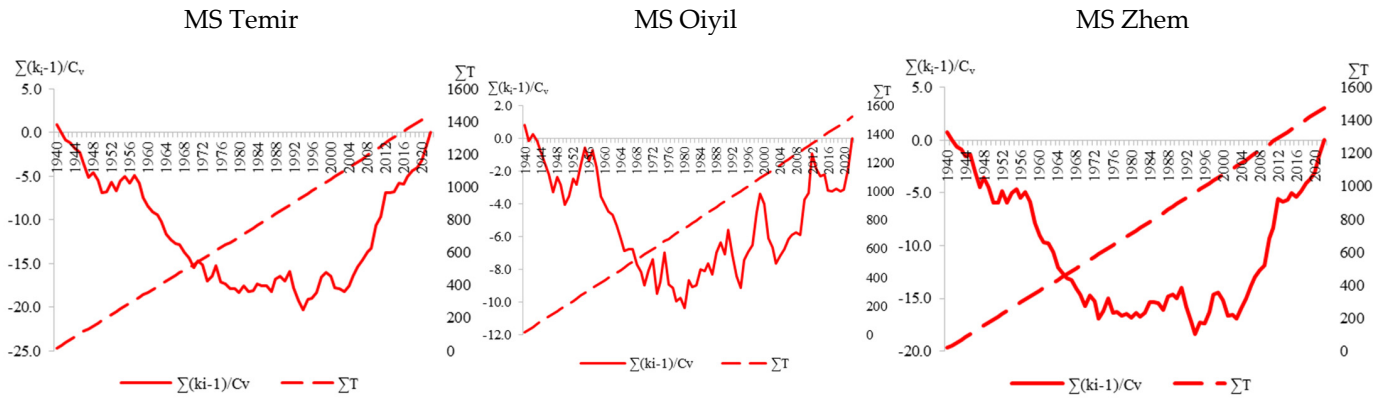

Figure 8. Integral curves of summer temperature.

The winter season is the main carrier of the climate signal. Winter temperatures are rising most intensively and monotonously: the cumulative increase is +2 … +3 °C for the period 1940–2022; the trends are significant at all stations ($p < 0.05$); the most rapid acceleration of warming occurred in 1975–1985, which is consistent with the years of structural breaks in winter Qmin (1985–1991).

The difference and total integral curves show a transition from a prolonged negative phase (1940–1970s) to a stable positive thermal anomaly, which persists until the end of the observation period. This reflects a change in the winter climate regime of the entire region.

The summer season shows a gradual and more variable warming. Summer temperatures also show a stable positive trend, but with much greater interannual noise: until the 1980s, there was an alternation of positive and negative phases; since the 1980s–1990s, a steady increase in the temperature background has been recorded; the variability of summer temperatures is higher than in the winter season.

Thus, the summer trend is pronounced but less clear-cut: it is forming gradually and is accompanied by high interannual contrast.

MS Temir: Until 1995, the temperature regime is stable around the average level; after 1995, the curve sharply breaks upward, marking the transition to a new climatic norm.

MS Oiyil: A gradual decline until the 1970s is replaced by a gradual increase; the changes are evolutionary in nature, without sharp jumps.

MS Zhem: A deep negative phase in the 1950s–1980s is replaced by a sharp and sustained warming after the 1980s, synchronous with the identified decrease in summer Qmin.

The integral curves of winter temperature are shown in Figure 9.

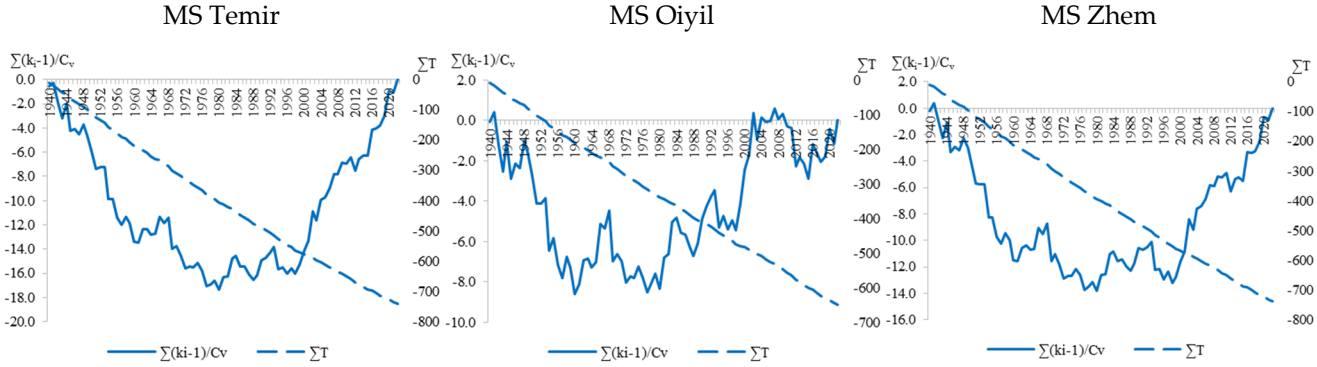

Figure 9. Integral curves of winter temperature.

Analysis of Figure 8 revealed a large-scale restructuring of the winter temperature regime, manifested in the transition of all rivers from the prolonged cold phases of the mid-20th century to steady warming since the late 1970s and 1980s, most pronounced on the Zhem river. The temperature regime of the region has undergone a profound restructuring: winter is the leading driver of climate change (a sharp, unambiguous, and early shift); summer is characterized by gradual but steady warming with high interannual variability; key climatic turning points (1975–1995) coincide exactly with moments of structural changes in minimum winter and summer runoff.

Thus, the identified long-term temperature phases represent the climatic basis for changes in minimum runoff and confirm the high sensitivity of the hydrological systems of the southern rivers of Western Kazakhstan to temperature.

3.2.4. Dynamics of Atmospheric Precipitation

The climatic dynamics of precipitation in the region show pronounced seasonal asymmetry: the summer regime is characterized by high fragmentation, while the winter regime is more uniform but undergoes structural changes that coincide with changes in minimum winter runoff [40].

Summer precipitation: The summer season is characterized by high interannual variability without a stable trend. Integral curves show an alternation of positive and negative phases lasting 10–20 years, reflecting the complex and unstable nature of circulation processes.

Summer precipitation is a key factor in the formation of Qmin, which is confirmed by the CSI_{min} typology; summer runoff is largely controlled by the precipitation regime.

Basin characteristics of minimum runoff vary: the Temir river shows a transition from the dry phase of the 1940s–1970s to stable summer moisture after the mid-1970s; the Oiyil river has a high amplitude of fluctuations combined with a deficit in 1950–1965 and a series of wet episodes in the 1980s–2000s, forming long-term increased moisture; the Zhem river experienced a prolonged dry phase until the mid-1970s, followed by a steady increase with the most contrasting phase structure. Thus, summer precipitation forms a mosaic climate environment that determines the fragmentation of summer Qmin and the high role of local precipitation events.

Winter precipitation: Unlike summer precipitation, winter precipitation is more uniform in nature, but integral curves show stable structural changes synchronous with the growth of winter Qmin.

The main basin features are that after a prolonged negative phase in the 1940s–1970s, the Temir river basin saw a sharp increase in winter moisture and the formation of a stable positive phase, while in the Oiyil river basin, the negative phase until the mid-1960s is replaced by a moderate increase in humidity with less pronounced fluctuations and a smoothed winter regime structure close to neutral; in the Zhem basin, a deep deficit until the early 1980s was replaced by a sharp and sustained increase in moisture, demonstrating the most intense and contrasting restructuring of the winter regime among all basins.

Despite the absence of pronounced trends, winter precipitation shows large-scale phase transitions that are synchronous with the increase in winter temperatures, the growth of minimum winter runoff, and the structural breaks of the 1970s–1990s.

Thus, it seems obvious that summer precipitation is characterized by high variability and pronounced phase fragmentation without a stable monotonic trend, which determines the increased seasonal vulnerability of minimum summer runoff (Qmin). Winter precipitation, on the contrary, has a more stable structure, but since the 1970s there has been a steady shift towards increased moisture, which correlates with an increase in minimum winter runoff. Summer runoff is mainly controlled by precipitation, while winter runoff is controlled by temperature, with the influence of winter precipitation manifesting itself mainly through large-scale climatic phases.

3.2.5. Seasonal Climatic Contrast

A comprehensive analysis of temperature and precipitation has revealed two fundamentally different climatic scenarios that determine the formation of minimum runoff in the arid basins of Western Kazakhstan. The winter scenario is a stable and directed climatic signal. The winter period is characterized by monotonous and intense warming which intensified after the late 1970s, a stable precipitation regime without prolonged deficit phases, and the formation of a prolonged positive climatic phase coinciding with the hydrological structural breaks of 1985, 1989, and 1991. The high consistency of the difference and total temperature and precipitation curves with the dynamics of winter Qmin indicates the dominant influence of the thermal factor, which determines the growth of minimum winter runoff in conditions of reduced freezing depth, increased infiltration, and increased winter groundwater recharge.

The summer scenario is characterized by a variable and fragmented climate regime. The summer season, on the contrary, demonstrates high interannual and interdecadal variability of precipitation; frequent alternation of dry and wet phases without stable regimes; multicyclical temperature changes, and the absence of a directed long-term trend until the 1980s. As a result, the climatic signal in summer is not synchronized with hydrological breaks, which explains the increased sensitivity of summer Qmin to precipitation and its internal fragmentation (short phases, high amplitudes, heterogeneous ITA/IPTA profiles).

This seasonal climatic asymmetry determines the differences in the internal structure of summer and winter minimum flow and serves as the basis for the interpretation given in the "4. Discussion" Section.

3.2.6. Relationship Between Climatic Parameters and Minimum Flow Dynamics

A comparison of the climatic typology (Section 3.1.5), the values of the climatic sensitivity index (CSI_{min}), and the integral climatic curves allows us to establish a clearly expressed seasonal nature of climatic control of minimum flow.

Winter period: single-factor climatic control. Winter minimum flow has a stable, unambiguous climatic determination.

Temperature control dominates in the Temir and Zhem basins: stable winter warming leads to a decrease in the depth of freezing, an increase in underground recharge, and an increase in Qmin. This is confirmed by the positive values of CSI_{min} and the phase reversal of winter integral temperature curves.

In the Oiyil basin, the guiding factor is winter precipitation, which is reflected in the negative values of CSI_{min} and the predominance of Qmin–P correlations.

Thus, winter climatic phases form two types of climatic control: temperature-based (Temir, Zhem) and moisture-based (Oiyil).

Summer period: multi-component and variable climatic signal.

During the summer season, climatic control of minimum runoff becomes more complex: summer precipitation, which is characterized by high interannual variability, plays a key role; the interaction of precipitation and temperature anomalies forms a combined climatic signal; CSI_{min} values in summer range from moderately negative to close to zero, reflecting the absence of a stable dominant factor; integral curves of summer precipitation are characterized by multiple phase changes and the absence of a long-term trend.

This explains the lower stability of summer Qmin and the high fragmentation of its internal structure.

Consistency with ITA/IPTA. The type of climate control fully corresponds to the internal organization of runoff:

Winter: ITA/IPTA profiles show long consecutive phases, low amplitudes, and high structural stability—a sign of runoff controlled by a single stable climatic driver.

Summer: profiles demonstrate fragmentation, high amplitude, and numerous phase transitions—characteristic of a climatically "disrupted" regime with variable drivers.

Climatic control of minimum runoff has a pronounced seasonal differentiation: in winter, control is unambiguous and stable (temperature or precipitation), while in summer, control is complex, variable, and precipitation-dominant.

This seasonal contrast directly determines the differences in the structure of minimum summer and winter runoff, as revealed in the previous subsections.

4. Discussion

The results obtained show that the restructuring of the minimum flow of the Temir, Oiyil, and Zhem rivers is due to a combination of regional climate change and local hydrogeological characteristics of the catchments. Rising temperatures, changes in precipitation patterns, and transformations in the frost–snow regime increase the vulnerability of minimum flow in arid conditions, which is consistent with recent studies documenting the degradation of low-water rivers in Eurasia under the influence of warming and aridization [41,42]. Spatial heterogeneity of precipitation and differences in groundwater recharge capacity amplify differences between basins and determine the nature of their response to climatic impulses.

The results are consistent with findings for Central Asia, where minimum flow is particularly sensitive to temperature changes and seasonal precipitation redistribution, as well as to changes in snow and permafrost processes [43,44]. The study basins are located at the southern edge of seasonal frost zones, making them particularly sensitive to winter warming: small temperature changes here can radically increase the proportion of liquid phase and enhance groundwater recharge [45]. This explains the identified synchrony of winter breaks and the consistency of winter trends between basins.

A key pattern is pronounced seasonal asymmetry. Winter minimum flow is influenced by regional temperature signals, as confirmed by synchronous structural breaks, stable

positive trends, and the high consistency of ITA/IPTA profiles. Summer minimum flow, on the contrary, is determined by local factors—convective precipitation, evaporation losses, and alluvial water storage capacity—which leads to fragmentation of summer series, asynchronous breaks, and negative trends. This duality corresponds to the concept of "dual climatic sensitivity" of rivers, according to which the cold season is governed by regional thermal trends, and the warm season by local precipitation circulation [46].

The differences between the basins are explained by their hydrogeological structure. Temir demonstrates maximum climate sensitivity due to weak buffering and high aridity, similar to the steppe basins of Mongolia and northern China [47]. Oiyil is characterized by increased resilience due to active groundwater recharge, which is consistent with data on the role of alluvial horizons as a climate buffer [48]. Zhem is the most vulnerable due to its conditions, as it combines high aridity and low water capacity, which limits its ability to compensate for climatic impacts, as in a number of basins in Central Asia [49,50].

Thus, the restructuring of minimum flow in the Temir, Oiyil, and Zhem basins is a multifactorial process in which climatic trends are combined with the geological and hydrogeological characteristics of the catchments. These results underscore the need for the comprehensive analysis used in modern hydrology [51] and allow for a reasonable interpretation of the identified differences in seasonal and inter-basin responses.

The asymmetry of the minimum flow response is determined by fundamental physical differences between the winter and summer seasons. In winter, riverbeds freeze partially or completely, the permeability of bottom sediments decreases, and the dominant role of groundwater and snowmelt recharge smooths out the climatic signal; the impact of extreme precipitation is minimal, and runoff reflects the climate of slow, inertial processes. In summer, on the contrary, high temperatures increase evaporation, convective rains are distributed extremely unevenly, riverbeds actively interact with groundwater, and short and often extreme periods of low water levels are formed, as a result of which summer runoff reflects the climate of fast, highly variable processes. These mechanisms are consistent with the concepts of seasonal hydrological regimes and process-based flow generation [52].

The values of CSI_{min} confirm the pronounced seasonal asymmetry of climate control: in winter, temperature is the dominant factor for most watersheds, while in summer, control is formed by a sedimentary or mixed regime. As a result, winter minimum flow responds primarily to regional climate signals, while summer flow is determined by local circulation and reflects spatially heterogeneous climatic conditions during the warm season. This is consistent with the ideas of the climate control of river systems developed in [46].

Seasonal asymmetry in minimum flow is a fundamental characteristic of arid river systems, in which summer and winter regimes function as two independent hydrological subsystems with different response scales: in winter, the system exhibits stability, synchrony, and a high degree of climatic integration, while in summer it becomes fragmented, locally controlled, and determined by high-frequency climatic influences. This explains the differences in trends, types of climate control, and structural properties of summer and winter Qmin, and also determines the specifics of adaptation and water management solutions for such basins.

The results show that differences in the dynamics of minimum flow in the Temir, Oiyil, and Zhem rivers cannot be explained by climatic factors alone. The hydrogeological structure of the catchments, the depth and dynamics of groundwater, the characteristics of channel sediments, and the peculiarities of channel–groundwater interaction form unique mechanisms for maintaining winter and summer flow in each basin.

Analysis of winter Qmin shows that the increase in winter minimum flow (after temperature breaks in 1977–1991) is primarily due to an increase in the proportion of groundwater recharge.

It has been established that the increase in winter temperatures leads to a gradual restructuring of the physical and hydrological conditions of the channel zone: the depth of seasonal freezing decreases, the duration of ice cover is reduced, the water permeability of channel sediments increases, and the hydraulic resistance of the "channel–groundwater" system decreases. Together, these processes increase the discharge of groundwater into the river network, contributing to the formation of a higher and more stable minimum winter flow.

This hydrogeological response reinforces the climatic trend, creating a new stable "winter norm" of flow, which is observed in the ITA/IPTA profiles.

The results obtained demonstrate that the long-term dynamics of the minimum flow of the Temir, Oyl, and Zhem rivers are formed under the influence of both short-term climatic fluctuations and long-term phase transitions characteristic of aridizing basins. The structural breaks identified by the Pettitt test are consistent with the phase shifts recorded by the ITA/IPTA methods and the RAPS integral curves, confirming the systemic nature of changes in the hydrological regime. The seasonal asymmetry of climate control, reflected in the CSI_{min}, highlights the different nature of summer and winter runoff formation: in summer, precipitation control dominates, while in winter, temperature and the related processes of freezing and underground recharge become decisive. Taken together, these results indicate that the minimum flow of the southern rivers of Western Kazakhstan is a highly sensitive indicator system that responds to both local climate anomalies and long-term changes in the regional climate.

Overall, the results of the study show that the minimum flow of the Temir, Oiyil, and Zhem rivers is formed under the influence of a combination of structural changes identified by statistical tests and long-term phase processes reflected by the ITA/IPTA and RAPS methods. Seasonal differentiation in climate control—precipitation control in summer and temperature control in winter—highlights the sensitivity of regional hydrological systems to contemporary climate trends. The identified structural shifts and sustained growth in winter runoff indicate a gradual restructuring of the inter-seasonal regime, which requires adaptive approaches to water resource management. These results provide a basis for formulating final conclusions and identifying prospects for further research.

The inclusion of ITA, IPTA, and RAPS methods fundamentally expands the interpretive capabilities of minimum flow research. While classical tests and trend analysis record the presence of breaks and the direction of changes, structural methods reveal the mechanism of their formation. ITA reveals the discrete phase organization of minimum flow and demonstrates the seasonal asymmetry of its internal structure, while IPTA reflects the integral evolution of these phases and allows us to trace the cumulative effect of successive climatic anomalies. RAPS, in turn, confirms the cumulative nature of flow restructuring and shows that the identified changes are the result of systemic climatic impact, rather than a combination of random extreme events. The coincidence of the extremes of the RAPS curves with the phase transitions of the ITA and the inflection points of the IPTA profiles indicates the consistency of the internal structure of the time series with regional climate trends. Thus, the ITA/IPTA/RAPS methods form a comprehensive analytical framework that allows us to move from the statistical recording of changes to their physical and climatic interpretation.

The geological and lithological structure of watersheds significantly determines their ability to accumulate moisture, maintain underground runoff, and smooth out climatic impulses. The Temir basin is characterized by highly permeable sandy-gravel channel

deposits and shallow groundwater levels, which ensure intensive discharge of groundwater and form a high hydraulic connection between the channel and groundwater systems. As a result, Temir responds to climatic changes with virtually no delay, corresponding to the type of highly connected fluvial–soil systems described by [45]. Oiyil, on the contrary, represents an inertial, hydrogeologically buffered system: powerful sandy loam and floodplain sediments, deep aquifers, and developed accumulation zones provide a significant capacity to smooth out climatic variability. This type of catchment corresponds to the concept of buffered aquifer-fed rivers [48], where underground recharge dampens climatic signals. The Zhem basin is the most arid and weakly connected: the alluvium is thin, the groundwater level is deep, and the connection between the channel system and the underground horizons is minimal. Under such conditions, minimum flow is almost entirely determined by summer precipitation and receives almost no recharge from groundwater. This structure corresponds to the class of ephemeral, intermittent disconnected systems characteristic of arid regions [40].

The study has several limitations that are important to consider when interpreting the results. First, the analysis is based on a long series of observations from stationary hydrological stations, which may contain gaps, hidden heterogeneity, and effects of changes in measurement techniques; it is impossible to completely exclude the influence of observational non-stationarity. Second, the study focuses on climatic factors, and changes in channel conditions, anthropogenic impacts, and landscape transformations were not taken into account in detail due to data limitations, which may affect the magnitude and dynamics of minimum flow. The third limitation is related to the use of linear trend and regression models, whereas hydrological systems often exhibit nonlinear and threshold responses. In the future, alternative methods, including nonlinear models, machine learning, and physics-based approaches, need to be tested. The fourth limitation concerns seasonal detail: the study does not include an extended analysis of winter processes (ice cover, ice regime, freezing dynamics), which may affect the interpretation of winter Qmin. Fifth, the influence of large-scale atmospheric regimes (ENSO, NAO, etc.) is assessed qualitatively, as long-term indices are only partially available. Finally, the conclusions are based on three basins and need to be verified using broader regional data. Nevertheless, the results obtained provide a reliable basis for further research and development of methods for analyzing minimum flow under conditions of climate instability.

Further research on minimum flow should focus on expanding spatial coverage, including additional stations, and using data from satellite missions (SMAP, GRACE-FO, MODIS) and reanalyses (ERA5-Land, MERRA-2) to refine climate–hydrological gradients. The development of quantitative models of groundwater flow and channel–groundwater interaction (MODFLOW, ParFlow, SWAT-GW) is promising, as it will allow for a more accurate assessment of the role of groundwater in the formation of winter Qmin.

It is necessary to introduce nonlinear and machine learning methods (GAM, SVR, Bai–Perron, XWT/WTC, Random Forest, CatBoost, Prophet) and the use of IPCC climate scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5) to build predictive models of minimum runoff. Integrating hydrological data with satellite information on soil moisture, surface temperature, and water reserves will make it possible to create a multi-component monitoring system and move to a comprehensive seasonal and interannual minimum flow forecasting system that strengthens the sustainability of water management planning in conditions of climate instability.

5. Conclusions

A comprehensive analysis of the minimum flow of the Temir, Oiyil, and Zhem rivers, including structural tests (Pettitt, homogeneity), stationarity (ADF), trends, climate typol-

ogy (CSI_{min}), and internal structure analysis methods (ITA/IPTA), revealed fundamental patterns of restructuring of low-water arid rivers in Western Kazakhstan under conditions of climate instability. Changes in minimum flow are systemic in nature and are determined by a combination of regional climate trends and the hydrogeological characteristics of watersheds.

1. The climatic nature of the restructuring of minimum flow. Winter minimum flow is a sensitive indicator of regional warming. An increase in winter temperatures of 1.5–2.5 °C reduces the depth of freezing, increases underground recharge, and forms a steady increase in winter Qmin. Synchronous structural breaks in winter runoff (1985–1991) coincide with climatic breaks, confirming a single regional driver. Summer minimum runoff is controlled by local variability in precipitation and evaporation; the breaks between basins are asynchronous, which corresponds to the spatially heterogeneous nature of summer moisture in arid conditions.
2. A hydrogeological moderating influence. The hydrogeological architecture of watersheds determines the form and scale of the climatic response. Temir is a system with high channel–soil connectivity and high permeability of channel sediments and hence strong temperature control of minimum runoff. Oiyil is a buffer watershed where powerful underground horizons smooth out climatic impulses. Zhem is the most fragmented system: low alluvial thickness, deep groundwater, and weak channel feeding make its runoff extremely sensitive to local precipitation and inter-seasonal climatic anomalies.
3. The internal structure of time series (ITA/IPTA). ITA/IPTA made it possible to reveal the hidden organization of minimum runoff, which is inaccessible to traditional statistical methods. Winter runoff is characterized by stable phases lasting 3–6 years, high symmetry, and minimal fragmentation—a reflection of the regional climatic signal. Summer runoff, on the contrary, is characterized by short phases (1–3 years), high amplitude, and structural instability, confirming its local and reactive nature. This emphasizes seasonal duality: winter is an integrator of the regional signal, while summer is a product of local processes.
4. The role of the RAPS method in assessing structural change. RAPS diagnostics revealed significant fluctuations in the intratemporal regularity of minimum flow and made it possible to quantitatively record periods of sustained elevated or reduced values, confirming the results of ITA/IPTA. Winter runoff is characterized by prolonged periods of positive deviations since the mid-1980s, consistent with the trend of winter warming. For summer runoff, alternating short negative phases were identified, reflecting the increasing role of drought episodes. The RAPS method complemented the structural analysis, providing independent confirmation of the phase shift in minimum runoff and strengthening the interpretation of the results obtained.
5. Methods for analyzing the internal structure of time series (ITA, IPTA) and the cumulative behavior of anomalies (RAPS) played a special role in interpreting the results obtained. Their combined application showed that the restructuring of minimum flow is formed not as a reaction to individual extreme years, but as a result of accumulated climatic impact, manifested through changes in the phase structure and integral dynamics of flow. ITA made it possible to identify discrete regime states and seasonal phase asymmetry, IPTA to track their long-term evolution, and RAPS to record the accumulation of positive and negative deviations, confirming the systemic nature of the transformation of the hydrological regime. Thus, the combination of these methods provides a more complete and physically sound understanding of the mechanisms.

6. A typology of climatic control. The CSI_{min} showed pronounced climatic differentiation. In winter, the runoff of Temir and Zhem is determined by temperature, while that of Oiyil is determined by a combination of temperature and precipitation. In summer, the Zhem river operates in a precipitation-controlled mode, while the Temir and Oiyil rivers demonstrate a mixed effect of precipitation and temperature. This confirms the existence of a dual climatic mechanism—temperature (winter) and precipitation (summer)—which manifests itself differently depending on the hydrogeology of the catchments.
7. A conceptual model of minimum flow restructuring.

The model shows that the restructuring of minimum flow is formed through a chain of interrelated processes: regional warming → change in the winter hydrological regime → transformation of the phase composition of precipitation → strengthening of the role of underground horizons → restructuring of the internal structure of time series.

Thus, minimum flow is an integral indicator of the climate–hydrogeological evolution of arid river systems, reflecting both regional climate trends and local characteristics of watersheds.

The results of the study are of significant practical importance for water resource management in arid areas. The identified seasonal asymmetry of minimum flow—a stable winter regime and a highly variable summer regime—allows for more accurate forecasts of low water levels, assessment of the risks of drought episodes, and water resource distribution strategies. The recorded structural breaks and long-term trends justify the need to revise the minimum ecological flow standards, taking into account the non-stationarity of the hydrological regime. RAPS analysis of the summer and winter low-flow time series of the Oyil, Temir, and Zhemrivers with clearly defined periods of water deficit and surplus identified that the summer flow of all three rivers exhibits a multi-period structure: for the Oyil, key low-flow periods occurred in 1975–1980, 1994–1997, and 2008–2010; for the Temir—1979–1983, 2000–2003, and 2015–2018; and for the Emba—1981–1985, 2001–2004, and 2014–2016. Following the phase shifts in the 1960s–1970s, a stable downward trend in summer low flows was established, driven by a combination of climatic factors—rising summer temperatures, reduced snow reserves, and changes in precipitation patterns—and anthropogenic impacts, including water withdrawals, land-use changes, and hydraulic regulation. Winter flows are characterized by a chronic deficit with dominant downward phases recurring at intervals of 15–25 years and weakly expressed recovery periods, indicating a structural insufficiency of the winter water regime. The recurrence and synchrony of deficit phases across all three rivers highlight the presence of common regional drivers, such as large-scale climatic cycles (NAO, ENSO), cyclical temperature and precipitation regimes, and anthropogenic pressures. Thus, the identified periods of low and high flow demonstrate a systematic nature of hydrological regime transformation in the small rivers of Western Kazakhstan, providing a basis for phase-based predictive modeling and the development of adaptive water resource management strategies under changing climate conditions.

The data obtained can be used in the design of hydraulic structures, where minimum flow is a key design parameter and requires adjustment for future climatic conditions. The final conclusions form the basis for the development of adaptation measures, increasing the sustainability of water management systems, and improving water-use practices in the context of increasing climate variability.

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draft preparation, A.A., L.B., M.T., B.I., M.D. and. S.B.; writing—review and editing, M.M., L.M. and A.M.; visualization, L.B.; supervision, A.M.; project administration, L.M.; funding acquisition, M.M. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

ADF	Augmented Dickey–Fuller Test
CSI	Climatic Sensitivity Index
CMIP	Coupled Model Intercomparison Project Phase 6
ITA	Intermediate Trend Analysis
IPTA	Integrated Intermediate Trend Analysis
MS	Meteorological Station

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