

Article

Flood Modelling of the Zhabay River Basin Under Climate Change Conditions

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Abstract: Flood modelling in snow-fed river basins is critical for understanding the impacts of climate change on hydrological extremes. The Zhabay River in northern Kazakhstan exemplifies a basin highly vulnerable to seasonal floods, which pose significant risks to infrastructure, livelihoods, and water resource management. Traditional flood forecasting in Central Asia still relies on statistical models developed during the Soviet era, which are limited in their ability to incorporate non-stationary climate and anthropogenic influences. This study addresses this gap by applying the Soil and Water Integrated Model (SWIM) to project climate-driven changes in the hydrological regime of the Zhabay River. The study employs a process-based, high-resolution hydrological model to simulate flood dynamics under future climate conditions. Historical hydrometeorological data were used to calibrate and validate the model at the Atbasar gauge station. Future flood scenarios were simulated using bias-corrected outputs from an ensemble of General Circulation Models (GCMs) under Representative Concentration Pathways (RCPs) 4.5 and 8.5 for the periods 2011–2040, 2041–2070, and 2071–2099. This approach enables the assessment of seasonal and interannual variability in flood magnitudes, peak discharges, and their potential recurrence intervals. Findings indicate a substantial increase in peak spring floods, with projected discharge nearly doubling by mid-century under both climate scenarios. The study reveals a 1.8-fold increase in peak discharge between 2010 and 2040, and a twofold increase from 2041 to 2070. Under the RCP 4.5 scenario, extreme flood events exceeding a 100-year return period (2000 m³/s) are expected to become more frequent, whereas the RCP 8.5 scenario suggests a stabilization of extreme event occurrences beyond 2071. These findings underscore the growing flood risk in the region and highlight the necessity for adaptive water resource management strategies. This research contributes to the advancement of climate-resilient flood forecasting in Central Asian river basins. The integration of process-based hydrological modelling with climate projections provides a more robust framework for flood risk assessment and early warning system development. The outcomes of this study offer crucial insights for policymakers, hydrologists, and disaster management agencies in mitigating the adverse effects of climate-induced hydrological extremes in Kazakhstan.



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1. Introduction

Global warming has led to an increase in the duration of the warm period, intensified seasonal snowmelt, and a higher frequency of floods and mudflows in Central Asian rivers since the mid-1970s [1]. The rivers of Central Kazakhstan are classified as Kazakh-type according to B.D. Zaikov and as exclusively snow-fed according to M.I. Lvovich's classification. The annual runoff of rivers in this region is generated almost entirely during spring floods, with spring runoff accounting for 95–98% of the total discharge. The initial rise in water levels during floods is usually gradual (up to 5–10 cm per day), but it then increases sharply, reaching 200 cm per day in an average year. Surface runoff is primarily formed by snowmelt, while rainfall generally contributes only marginally to runoff during the flood period. In summer, the air humidity deficit and soil dryness are so extreme that rainfall is almost entirely absorbed by the upper soil layer or lost to evaporation, having little effect on runoff. Only intense rain events, with a precipitation layer of 30–50 mm or more, can generate floods. Rain-induced floods occur approximately once every 3–5 years, usually in June or July, and typically last no more than 5–10 days.

The extreme irregularity of runoff in the plains of Kazakhstan increases flood risk. Between 1991 and 2012, 437 extreme hydrological events were recorded in the country, including floods caused by flood waves, heavy rainfall, and ice-jam phenomena [2]. These events affected 9600 people, with total damages estimated at KZT 20 billion. One of the most severe water-related disasters occurred in 1993, when floods and waterlogging impacted 669 settlements, destroying 635,000 m² of housing. The direct economic damage exceeded USD 500 million. In recent years, the frequency and severity of flood events have increased significantly, as evidenced by catastrophic floods on the Syr Darya River (2004–2007), in East Kazakhstan (2010), in West Kazakhstan on the Zhaiyk River (2011, 2024), and on the Zhabay River (2014, 2017, 2024) [3,4].

In the Republic of Kazakhstan, significant attention is given to the prevention of dangerous natural phenomena. Emergencies caused by spring and rain-induced floods account for approximately 30% of all emergencies, which is twice the recurrence rate of those caused by hazardous meteorological phenomena. More than 50% of the total number of people affected by emergencies in the republic are impacted by spring and rain floods [5]. As a result, at the current stage of Kazakhstan's development, one of the most critical tasks is reducing flood risk, which is considered a strategic risk. Flood-related damage depends not only on water levels in reservoirs and watercourses but also on the predictability of upcoming floods. The availability of early and sufficiently accurate flood forecasts enables authorities to plan and implement preventive measures to mitigate or avoid flood damage. Of particular importance is the study of modern changes in the conditions of maximum runoff formation. Furthermore, there remains a gap in applying high-resolution, process-based modelling approaches to assess future hydrological extremes in these regions.

Despite the existence of flood mapping alternatives offered by geomorphic methods that have not been used generally in Kazakhstan, recent studies have employed numerical methods to assess and project river streamflow under climate change conditions [6–10]. These studies have focused on various river basins, including the Zhabay, Derkul, Shagan, Sarysu, Tobol, Buktyrma, Ulbi, and Oba, which are located in diverse natural zones with varying topography, catchment sizes, and runoff regimes (nival, glacio-nival, and nival-glacial). Additionally, in Kazakhstan, Ref. [11] developed a conceptual dynamic model for

mountain river runoff, while canonical decomposition methods [12–15] have been applied in hydrological research. Furthermore, a model intercomparison study was conducted within the ISIMIP project in which SWIM was compared with other regional-scale hydrological models across 12 major river basins worldwide. These included the Rhine, Tagus, Niger, Blue Nile, Ganges, Lena, Upper Yellow, Upper Yangtze, Upper Mississippi, Mackenzie, Upper Amazon, and Darling [16].

The use of modern modelling methods provides an alternative to traditional approaches, particularly in regions with sparse hydrological networks and limited data coverage. Kazakhstan, where the density of meteorological stations is one per 10,400 km², falls short of the World Meteorological Organization (WMO) standard, which recommends one station per 4000 km². Similarly, the average density of hydrological stations in Kazakhstan is one per 8282 km², which is insufficient for effective hydrological monitoring and forecasting. For example, in the Yesil River basin, which includes the Zhabay River, 78 hydrological stations were operational in the past. However, today, only 43 hydrological posts remain. The current hydrological network, both in number and density, is inadequate to support real-time information services and hydrological forecasting. According to WMO guidelines [17], which define the minimum necessary hydrological network based on regional physical-geographical conditions and economic development, Kazakhstan does not meet the required hydrological monitoring standards. The lack of data significantly hinders comprehensive monitoring of hydrometeorological changes. Therefore, hydrological modeling has become an essential tool for generating reliable, long-term river runoff forecasts [18].

This study focuses on the Zhabay River basin, particularly the city of Atbasar, which is highly vulnerable to hydrological hazards, including extreme water levels that can flood populated areas and damage infrastructure. The Zhabay River basin exhibits significant seasonal and long-term flow variability, creating challenges for efficient water resource management and resulting in substantial damage, as demonstrated by the floods of 2014, 2017, and 2024 in Atbasar City [19]. In April 2017, heavy rain and strong winds caused a sharp rise in water levels to 6.1 m, generating a destructive flood wave. This led to the failure of a protective dam at four locations and the flooding of over 400 houses, forcing the evacuation of 1374 people. The 2017 water level in the Zhabay River exceeded the 2014 flood level by 80 cm and surpassed the critical level of 3.45 m by 2.6 m [20]. The most severe flood in Atbasar's history occurred in April 2014, when rapid warming and intense melting of steppe snow resulted in the flooding of 559 houses across 12 city streets [21,22].

One of the main gaps in current hydrological research in Kazakhstan is the lack of detailed modelling studies focusing on small- and medium-sized snow-fed basins, such as the Zhabay River. These basins are highly vulnerable to climate change-induced hydrological extremes, yet existing research has primarily addressed larger river systems. Understanding potential changes in flood frequency and magnitude in the Zhabay River is crucial for improving flood management strategies and ensuring water security in the region. This study addresses this gap by applying the Soil and Water Integrated Model (SWIM) to analyze the impact of climate change on hydrological extremes in the Zhabay River basin. SWIM simulates key hydrological processes, including snowmelt, soil moisture dynamics, and groundwater interactions, making it well-suited for evaluating seasonal and long-term runoff variations in snow-fed rivers. By integrating bias-corrected climate projections under RCP 4.5 and RCP 8.5 scenarios, this study establishes a robust framework for assessing future flood risks and informing water management strategies.

The research methodology includes calibrating and validating SWIM using historical climate and hydrological data from the Atbasar gauge station. The model is then driven by an ensemble of General Circulation Models (GCMs) to simulate river discharge trends for

the periods 2011–2040, 2041–2070, and 2071–2099. This approach provides a comprehensive assessment of runoff variability, potential flood magnitudes, and frequency changes under different climate scenarios.

Modelling and assessing long-term runoff in this basin are essential for effective water resource management. This study evaluates the impact of climate change on average annual runoff and flood patterns until the end of the century. The results can support various water management activities, including public safety measures against extreme hydrological events (floods and droughts) and the addressing of challenges related to water resource management, protection, and sustainable use. Additionally, these findings can contribute to Kazakhstan's role in developing interstate water cooperation frameworks in Central Asia. Modelling based on international climate change scenarios will enable relevant organizations, such as the Emergency Committee of the Republic of Kazakhstan, water management authorities, and hydraulic engineering companies, to receive advance warnings about potential high or low water levels. This early warning system will facilitate the timely implementation of preventive measures, helping to mitigate the impacts and consequences of adverse hydrological phenomena. The expected outcomes of this study include (1) an improved understanding of how climate change will affect peak flood events in the Zhabay River basin, (2) quantitative projections of future river discharge variability, and (3) recommendations for flood risk management and adaptation strategies. These findings will be instrumental in supporting water resource planning and disaster preparedness efforts in Kazakhstan, particularly for communities vulnerable to extreme hydrological events.

2. Materials and Methods

2.1. Study Area

The Zhabay River is a right tributary of the Yesil River, with a drainage area of 8800 km² and a length of 196 km. The average drainage elevation is 364 m, and the river network density is 0.11 km/km². The elevation difference from the source to the mouth is 233 m, resulting in a relatively low average slope of 1.2 m/km. The river's main tributaries include:

- Sarkrom (Sarymsakty)—drainage area: 1500 km², length: 79 km
- Ashyli—drainage area: 1060 km², length: 58 km
- Zhilandinka (Kerege-Tas)—drainage area: 3650 km², length: 140 km

The Zhabay River channel is weakly branched, with a radius of 10–50 m, but the stream width is often only a few meters. The average annual discharge at the mouth is 8.04 m³/s, while the maximum instantaneous discharge can exceed 1000 m³/s. The water level typically rises 4–6 m during high-flow periods. The upper reaches of the river dry up annually, and in winter, the river freezes along the banks. Ice formation is common, with winter ice thickness averaging 120–140 cm; in extreme winter conditions, it can reach 160–180 cm. However, spring ice drift is not pronounced and does not occur every year. The Zhabay River exhibits both seasonal and long-term flow variability. Peak discharges were recorded on 11 April 2014 (1750 m³/s) and 17 April 2017 (3290 m³/s). The lowest recorded discharges occurred during the open-channel period on 8 August 1969 (0.5 m³/s) and in winter on 3 April 1969 (0.95 m³/s) [23].

The Atbasar hydrological station was selected for model calibration and research analysis (Figure 1).

The five nearest hydrological stations were selected for further studies of the Zhabay River catchment area. These stations—Balkashino, Atbasar, Zhaltyr, Akkol, and Shchuchinsk—have observation records exceeding 80 years (Table 1).

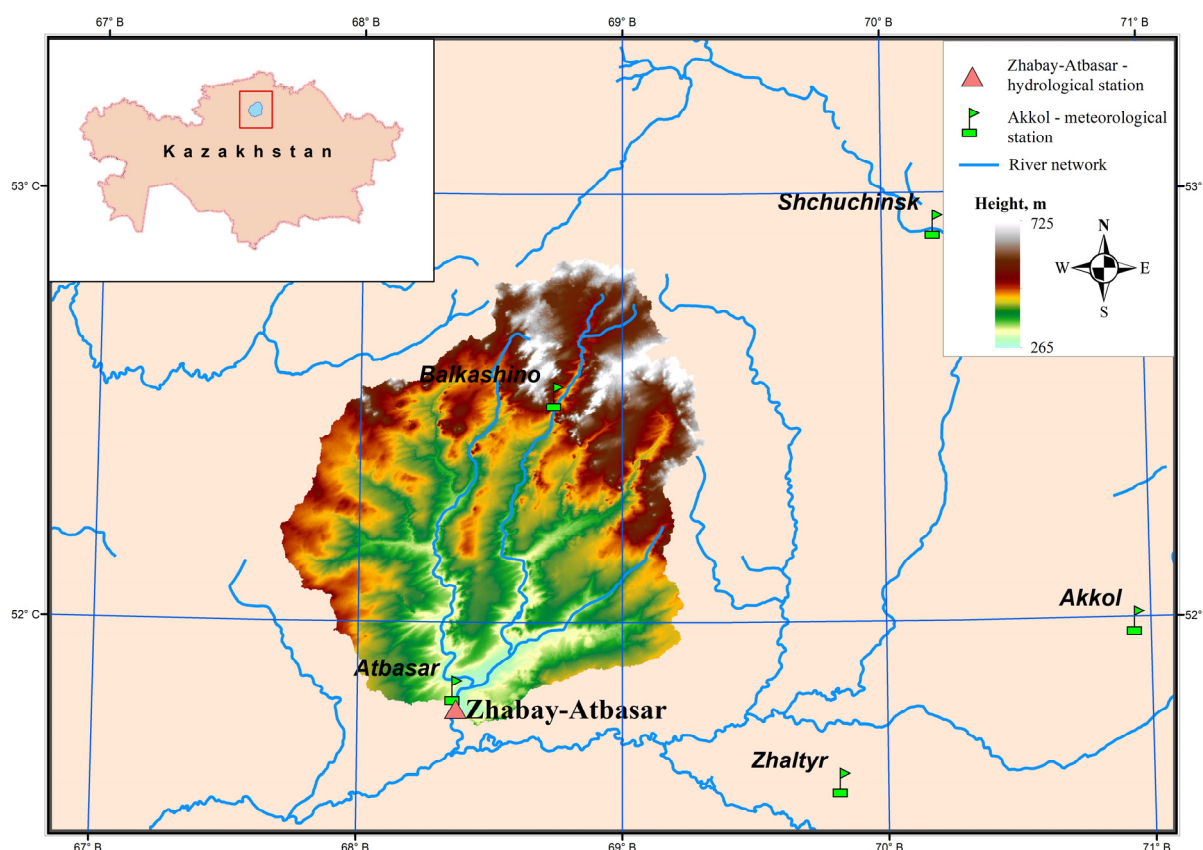


Figure 1. Location of the study area—Zhabay River basin.

Table 1. Selected meteorological stations in the Zhabay basin.

Station Name	Longitude	Latitude	Height (m)	Observation Period	Long-Term Average Temperature (°C)	Long-Term Precipitation (mm)
Akkol	70.94	51.99	383	1909–present time	1.93	346
Atbasar	68.36	51.84	302	1886–present time	2.00	295
Balkashino	68.74	52.53	398	1934–present time	1.33	376
Zhaltyr	69.82	51.63	304	1940–present time	2.57	319
Shchuchinsk	70.20	52.93	393	1934–present time	1.57	324

According to the World Meteorological Organization (WMO), over the last 50 years, global temperatures have increased at a rate of 0.13 °C per decade. Analysing changes in the thermal regime of individual regions reveals that modern warming is observed almost everywhere, though its intensity varies. The most significant changes have occurred over continental regions between 40 °N and 70 °N, particularly in dry, arid areas. Kazakhstan, situated in the mid-latitudes of the Eurasian continent and far from the influence of oceans, is warming at a significantly higher rate than the global average. Since 1976, the global average annual air temperature has increased by 0.18 °C per decade, whereas in Kazakhstan, the rate is much higher—0.32 °C per decade [24]. The most pronounced warming is observed in the western region, where temperatures have increased by 0.47–0.54 °C per decade. In the Yesil River basin, which includes the Zhabay River, seasonal temperature trends show the following increases: 0.43 °C per decade in winter; 0.44 °C per decade in spring; 0.19 °C per decade in summer; and 0.46 °C per decade in autumn.

Annual precipitation in the Yesil River basin has increased to 300–380 mm, with maximum precipitation occurring in summer and minimum precipitation in winter, displaying

high seasonal variation. Warm-season precipitation is 2.5–3 times higher than cold-season precipitation. At the Astana meteorological station, total annual precipitation is 308 mm, with 219 mm occurring during the warm half of the year. The mean square deviation in precipitation varies seasonally: July: 25–30 mm, with a maximum of 42 mm at Petropavlovsk station; February: 5–10 mm, with a minimum of 4 mm at Yesil station. The precipitation regime has changed unevenly across Kazakhstan, varying by season and region. In the Yesil River basin, winter precipitation has increased significantly, while annual precipitation anomalies show only minor positive trends (0.1–0.4 mm per decade). Linear trend analysis of annual and cold-season precipitation anomalies indicates no significant long-term changes or identifiable trends.

The study also observed that cold-season surface air temperature has increased at a rate of 0.5–0.6 °C per decade. However, several years with anomalously low winter temperatures were identified, including 1968–1969, 1976–1977, 1984–1985, and 1993–1994, when negative anomalies ranged from −7 °C to −2 °C. Figure 2 illustrates the interannual variation in seasonal air temperatures and precipitation at selected meteorological stations.

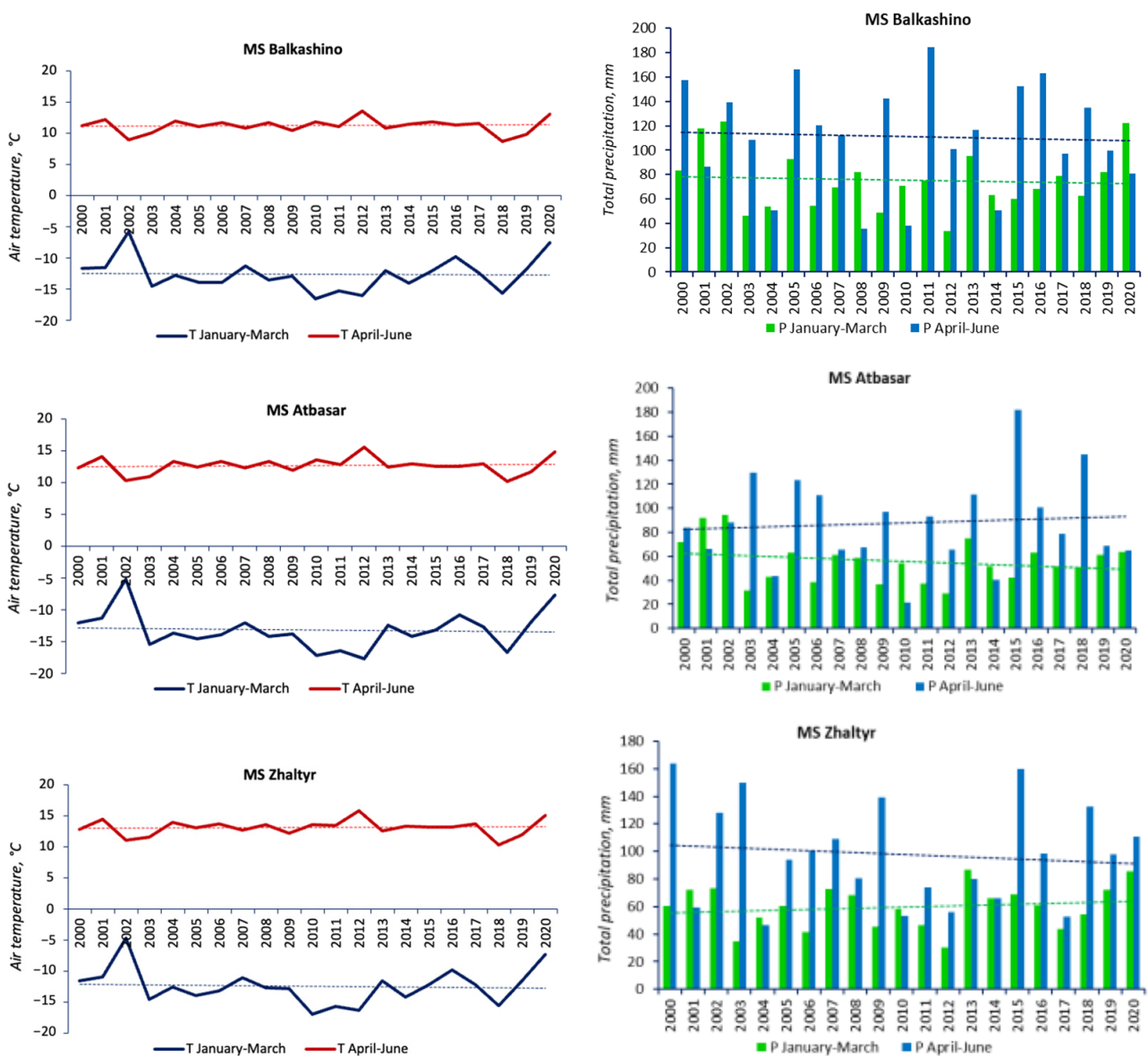


Figure 2. Cont.

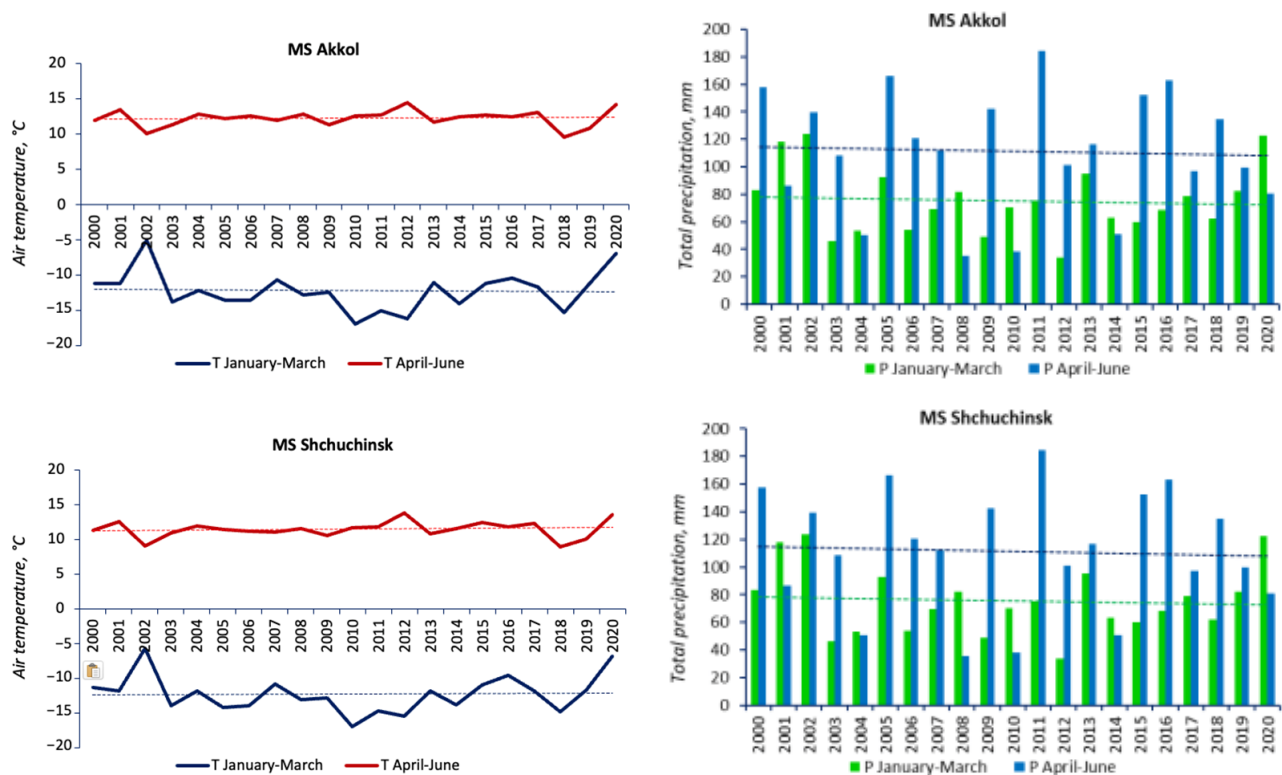


Figure 2. Interannual variation of seasonal values of air temperature and precipitation.

An analysis of the data in Figure 2 reveals a slight increasing trend in January–March temperatures since 2012. However, there is no significant trend in April–June air temperature changes. Similarly, cold-season precipitation shows no discernible trend, while a slight decrease is observed during the warm season (April–June). A comparison of average long-term air temperatures between the periods 1980–2000 and 2001–2020 indicates a significant warming trend in the Zhabay-Atbasar river basin. The average annual temperature has increased by 1.1 °C, with the most notable warming occurring in March (+3.14 °C) and November (+2.43 °C). In contrast, October’s temperature has shown relatively little change.

2.2. Modeling Application

A wide range of hydrological models exist for river catchments, varying in complexity from simple empirical models to complex mathematical models that represent all stages of the river basin water balance. Based on their principles and methodological approaches, hydrological models are classified into deterministic (physical, physically based, dynamic) and stochastic (probabilistic, statistical) models. Deterministic models describe physical processes occurring in the real world, where model parameters can be measured in the field. In contrast, stochastic models rely on probability theory and mathematical statistics, functioning as ‘black box’ systems that reproduce random (stochastic, probabilistic, statistical) structures.

A comparison of the most widely used hydrological models in global practice is presented in Table 2.

Table 2. Comparison of the most used hydrological models in the world practice.

Model Name	Country of Origin	Scale	Advantages	Restrictions
SAC-SMA—Sacramento Soil Moisture Accounting model [25,26]	USA	Catchment	Easy to use for operational prediction.	Limited ability to model spatial variability.
PRMS—Precipitation Runoff Modelling System [27,28]	USA	Watershed, regional	The modular structure allows the model to be adapted to specific conditions.	Requires detailed input data. Difficult to set up and calibrate for large regions.
SWAT—Soil and Water Assessment Tool [29,30]	USA	Watershed, regional	Ability to model long-term impacts. Integration with GIS for spatial analyses.	High requirements for the volume and quality of data.
SHE—Système Hydrologique Européen [31,32]	Europe	Watershed, regional	Detailed representation of physical processes. Flexible customisation for different conditions.	High computational costs. Complexity in calibration and validation.
HBV—Hydrologiska Byråns Vattenbalansavdelning [33,34]	Scandinavia	Local/Region	Easy to calibrate and adjust. Applicable in various climatic conditions.	Limited ability to account for complex hydrological processes, such as surface and groundwater interactions. Developed for mountain rivers. Possibility to use stations only within the catchment area
SWIM—Soil and Water Integrated Model [35,36]	Germany	Watershed, regional	Integrated approach to modelling ecosystem processes. Ability to analyse land use and climate change scenarios. Possibility of using meteorological stations outside the catchment area.	High complexity, requiring significant computational resources.
Tank model [37,38]	Japan	Local and catchment	Simple structure and application. Small data requirements.	Limited ability to model complex hydrological processes.
Xinanjiang [39,40]	China	Catchment	Effectiveness in modelling runoff in humid regions.	Limited applicability in arid regions. Requires adaptation to different climatic conditions.
ECOMAG—ECOLOGical Model for Applied Geophysics, runoff formation model [41,42]	Russia	Watershed, regional	Integration of geophysical data. Ability to model complex ecosystem processes	High demands on data and computing resources. Difficult to set up and calibrate.

Table 2. *Cont.*

Model Name	Country of Origin	Scale	Advantages	Restrictions
Hec-Ras [43,44]	USA	Local and regional	Allows modelling of both one-dimensional and two-dimensional flows. Suitable for flood risk analysis and infrastructure design.	High requirements for the quality of topographic and hydrological data. Long calculation time when modelling large regions.
FastFlood [45]	The Netherlands	Local and regional	High calculation speed. Can be used in data-poor environments. Suitable for rapid response in floods.	Limited detail of modelled processes. Dependence on the correctness of training data and machine learning models.

For this study, the Soil and Water Integrated Model (SWIM), developed by the Potsdam Institute for Climate Impact Research (PIK), was employed [30]. SWIM has been widely used globally, particularly for assessing the impact of climate change on river discharge in the Elbe River basin [46,47], as well as other European river basins, including the Tagus, Emajoki, Lule, Rhine, Danube, Samara, Teteriv, Western Bug, Tay, and Northern Dvina [48]. The model has also been applied to climate risk assessments for irrigated agriculture in the Aral Sea basin [49], as well as to support agricultural and water management adaptation strategies in the Upper Tarim River basin, China [50]. Additionally, Ref. [51] investigated its applicability in the upper and middle Wuyuer River basin, China, while the impact of climate change on river discharge was also evaluated in four large African river basins [52].

SWIM is a medium-complexity model designed for river basin and regional scales. It offers a more comprehensive representation of interrelated hydrological, vegetation, and nutrient processes compared to standard hydrological models. The model is based on publicly available regional data and is easier to parameterize than more complex hydrological models. One of its key advantages is its ability to integrate underlying surface data, including land use patterns, biophysical parameters, soil structure, and seepage data. Additionally, SWIM can utilize meteorological data from stations outside the catchment area, as it allows for data interpolation to cover the entire basin. SWIM was selected for application in this study regarding its key advantages:

- Detailed hydrological modelling—Incorporates soil composition, depth, porosity, and maximum water-holding capacity, as well as land use data, which are often absent in continental-scale and large-scale water resource models.
- Accurate representation of vegetative processes—Unlike many hydrological models, SWIM accounts for dynamic vegetation processes in climate change studies.
- Enhanced modelling of land use, agricultural management, and crop yields—Provides a more detailed representation of climate and land use interactions, improving the accuracy of feedback assessments.

2.3. The SWIM Model: Input Data

The Soil and Water Integrated Model (SWIM) is an eco-hydrological model built upon the foundations of SWAT (Soil and Water Assessment Tool) [53] and MATSALU. It integrates deterministic, process-based approaches to simulate key hydrological cycle processes, including vegetation growth, nutrient cycling, and sediment transport at the river basin scale [53]. SWIM operates on a continuous-time basis and utilizes a three-level

spatial disaggregation scheme: basin, sub-basin, and hydrotape (or hydrological response unit, HRU)—to model complex interactions within these systems. It functions with a daily time step.

Over two decades of application, SWIM has proven its adaptability and effectiveness in various geographical regions and applications, including Europe, Asia, and Africa [54,55]. It has been instrumental in addressing a wide range of hydrological issues, such as floods, droughts, and climate impact studies, and has been extended with specific modules for simulating reservoir operations and irrigation impacts [28,56–58]. Currently, SWIM incorporates the following processes for simulating the thermal and water regimes of various land ecosystems (Figure 3):

- Interception of liquid and solid precipitation by vegetation, including subsequent evaporation, melting, or freezing.
- Snow cover formation under forest canopies and open areas during the cold season, encompassing accumulation, evaporation, melting, and potential refreezing of meltwater.
- Surface runoff generation and soil infiltration of liquid precipitation or melted snow.
- Water balance dynamics in the aeration zone, including transpiration, soil evaporation, groundwater exchange, and changes in soil moisture.
- Heat balance and thermal regime, including soil freezing and thawing processes.

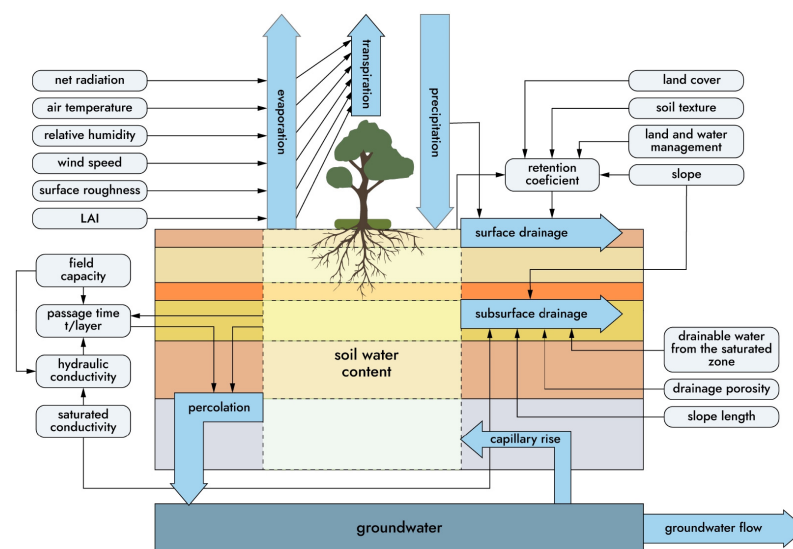


Figure 3. SWIM model structure diagram (PIK, User Manual, 2024).

All necessary data and observations for modelling were collected for the study area, including:

- Climate parameters, such as daily maximum, average, and minimum air temperatures, precipitation, average wind speed, relative humidity, and total solar radiation. These meteorological characteristics were obtained from the official website of Republican State Enterprise (RSE) “Kazhydromet”, covering the period from the beginning of instrumental observations to 2020 [59].
- Digital Elevation Model (DEM) maps, provided by the Consultative Group for International Agricultural Research (CGIAR).
- Vegetation and land use maps, sourced from MODIS-Globeland30 [60].
- Soil type maps, obtained from the Food and Agriculture Organization (FAO) [61].

A 90-m resolution DEM, derived from Shuttle Radar Topography Mission (SRTM) data, was used to analyse the basin’s relief, including flow direction, local depressions, flow

accumulation, and stream identification and ordering. The basin was classified into 12 land use types, based on GlobeLand30, and 5 soil types, according to the FAO classification.

Figure 4 presents the land use map and soil type map, respectively, for the study area, including a 10-km buffer zone.

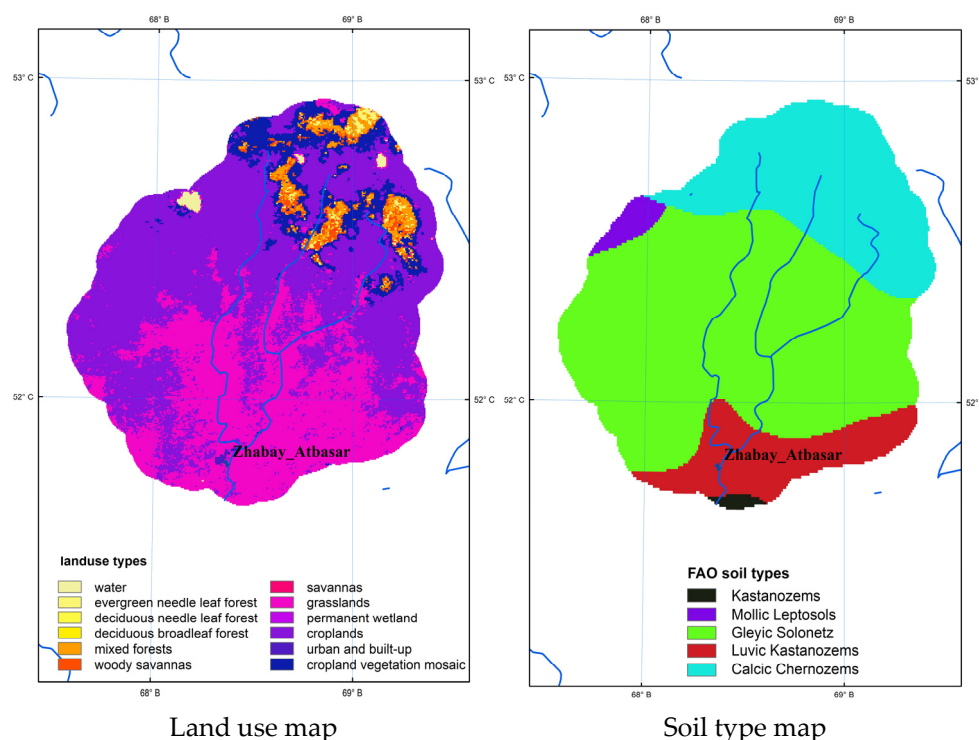


Figure 4. Maps of land use and soil types of the Zhabay River catchment area.

During this study, the SWIM hydrological model was adapted to the specific conditions of the Zhabay River basin. The model was then calibrated and validated to ensure its accuracy in simulating historical hydrological processes. A key factor in model calibration is the selection of meteorological stations whose data most accurately reflect the river's water regime. To calibrate the model parameters effectively, a homogeneous dataset with continuous hydrometeorological records, free from omissions and errors, is required. Data from the Zhabay River hydrological post in Atbasar City were analysed, while cadastral materials from RSE "Kazhydromet" were used to assess water resources in the Zhabay River [62]. The spatiotemporal distribution of runoff was examined from the beginning of instrumental observations to 2020.

Meteorological data were sourced from five meteorological stations in the study area, as listed on the RSE "Kazhydromet" website (Table 1) [59]. After calibration, the model was applied to simulate river discharge under various climate change scenarios, providing insights into future hydrological conditions. The simulated results were then analysed to assess the model's performance and the potential impacts of climate change on the river basin. To ensure the model's reliability and efficiency, the following statistical indicators were calculated for the historical period:

- Nash-Sutcliffe Efficiency (NSE)
- Percent Bias (PBIAS), following the method of D. Moriasi [63]
- Coefficient of Determination (R^2) [64]

Careful testing and quality control are critical for the practical application of the model [8,65].

2.4. Methods of Testing Series for Homogeneity

Hydrometeorological calculations and statistical analysis were conducted using standard software packages, including MS Excel and Statistica 13.3. The homogeneity of time series data was assessed through genetic and statistical analyses, employing various statistical tests. Genetic analysis examines the structure of multi-year fluctuations in hydrometeorological characteristics, identifying physical causes of potential data heterogeneity. Before applying statistical methods, difference integral curves were constructed to analyse long-term fluctuations, assess changes in mean values and variability over time, and detect possible inconsistencies in the dataset. Statistical homogeneity refers to the condition where elements of hydrometeorological characteristics and their parameters (mean value, variance, and autocorrelation) belong to the same population. In line with international best practices, a combined statistical approach is recommended for assessing time series homogeneity [66].

In this study, the following tests were applied to determine the homogeneity of empirical hydrometeorological time series: Standard Normal Test (Alexandersson's Test); Buishand's Test; nonparametric Pettitt's Test; Von Neumann Ratio; and Student's *t*-test.

The selection of these tests was based on their complementarity, robustness to different types of changes in data, and extensive validation in hydrology and climatology.

- Student's *t*-test: Detects significant shifts in mean values, which is critical for analysing potential anthropogenic or climatic changes. The test compares the calculated statistical value for homogeneous consecutive segments of the dataset with a critical reference value at a significance level of 5%, corresponding to a 95% confidence level.
- Alexandersson's Test: Particularly effective for identifying discontinuities in mean values under gradual changes in observational conditions, making it one of the most widely recommended methods in global hydrological and climatic studies.
- Buishand's Test: Identifies breakpoints in the time series without prior knowledge of their occurrence, making it suitable for analysing irregular hydrological changes.
- Pettitt's Test: A non-parametric approach that does not require assumptions about normal data distribution, making it resistant to outliers and anomalies, which are common in hydrometeorological datasets.
- Von Neumann Ratio: Based on autocorrelation analysis, this test assesses the degree of variability within the dataset and helps detect latent trends that may not be apparent through mean shifts alone. Heterogeneity can manifest not only through abrupt changes but also in structural variations in the data.

This integrated approach eliminates false conclusions arising from the use of only one method and meets international standards for verification of climatic and hydrological series, ensuring high reliability of the analysis.

1. Student's criterion. The assessment of the homogeneity of hydrometeorological observation series using Student's *t*-test (for mean values) involves comparing the calculated test statistic for homogeneous consecutive segments of the series, derived from empirical data, with its critical reference value, considering the significance level, sample size, autocorrelation, and asymmetry coefficients. The significance level is typically set at 5%, meaning the null hypothesis of time series homogeneity is accepted with a 95% probability.

The calculated value of Student's *t* criterion statistic is determined by the following formula:

$$t = \frac{\bar{y}_1 - \bar{y}_2}{\sqrt{n_1 \times \sigma_1^2 - n_2 \times \sigma_2^2}} \times \sqrt{\frac{n_1 \times n_2 \times (n_1 + n_2 + 2)}{n_1 + n_2}} \quad (1)$$

where $\bar{y}_1$, $\bar{y}_2$, σ_1^2 , and σ_2^2 are the mean values and dispersions of two consecutive samples, respectively; n_1 , n_2 are the sample volumes.

Assessment of homogeneity (stationarity) by Student's criterion is carried out by comparing the calculated values and critical values of statistic t .

2. Alexandersson's test. The series is divided into two parts containing k and $n - k$ terms:

$$T(k) = k\bar{Z}_1^2 + (n - k) \cdot \bar{Z}_2^2 \quad k = 1, \dots, n \quad (2)$$

$$\bar{Z}_1 = \frac{1}{k} \sum_{i=1}^k \frac{(Y_i - \bar{Y})}{S} \quad (3)$$

$$\bar{Z}_2 = \frac{1}{n - k} \sum_{i=k+1}^n \frac{(Y_i - \bar{Y})}{S} \quad (4)$$

where S is the mean square deviation

If homogeneity violation occurred in year K , $T(k)$ reaches a maximum near year $k = K$. The obtained values are compared with the critical values.

3. Buishand's test. If the violation of homogeneity of the series occurred around year K , then S^*k reaches a maximum (in case of positive shift) or a minimum (in the case of a negative shift) near the year $k = K$.

$$S_\lambda^* = \sum_{i=1}^k (Y_i - \bar{Y}) \quad k = 1, \dots, n \quad (5)$$

$$R = (\max S_k^* - \min S_k^*) \quad 0 < k < n \quad (6)$$

The obtained values are also compared with the critical values.

4. Nonparametric Pettitt's test. Ranks $r_1, \dots, r_n$ (numbers in the ranked series) of meteorological quantities $Y_1, \dots, Y_n$ are used to calculate the statistics X_k .

$$X_K = 2 \sum r_i - k(n + 1) \quad 0 < k < n \quad (7)$$

$$X_E = \max |X_K| \quad 1 < k < n \quad (8)$$

5. Von Neumann relation.

$$\sum_{i=1}^{n-1} (Y_i - Y_{i+1})^2 / \sum_{i=1}^n (Y_i - \bar{Y})^2 \quad (9)$$

The Von Neumann test characterises a series as homogeneous if N is close to 2. For an inhomogeneous series, N is less than 2.

2.5. Methods to Analyse the Streamflow

The analysis of multi-year changes in hydrometeorological characteristics is based on the use of difference-integral curves. Normalised values are employed to identify long-term dynamics, including the synchrony of observed changes through pairwise correlation matrices and linear determination coefficients, allowing for the identification of phases of increased and decreased water availability. The analysis of multi-year fluctuations in hydrometeorological characteristics includes the assessment of quasi-periodicity, trends, and statistical homogeneity of the series. Difference-integral curves are widely used to determine phases of increased and decreased water availability in water bodies, as well as the moments of phase transitions. However, it is important to note that these curves illustrate the accumulated anomaly only relative to the sample mean. The analysis of

river flow dynamics in the study region indicates that flow fluctuations occur cyclically, a phenomenon widely recognized by researchers [67].

Theoretically, if the trend in multi-year fluctuations of hydrometeorological characteristics is climate-driven, it could be used for forecasting purposes. However, studies conducted at the State Hydrological Institute have shown that runoff forecasting based on the extrapolation of trend and cyclic components is highly problematic and often unreliable. Extrapolation of identified trends in long-term hydrological characteristics is typically based on a linear trend analysis. However, statistically significant trends in river runoff are rare on a global scale [68].

The difference-integral curve of the annual water flow calculated by Equation (10) [69]:

$$\Sigma(k_i - 1)/Cv \quad (10)$$

where k is the annual values of river runoff, and Cv is the coefficient of variation characterising variability of annual runoff; it is an indicator reflecting the degree of unevenness of annual runoff by years.

Statistical methods for analysing river runoff time series are used to identify phases of high and low water availability (high-water and low-water periods). The primary objective is to determine periods when annual runoff values deviate significantly from the long-term average. The empirical probability of maximum annual runoff is a crucial tool for assessing extreme hydrological events, such as floods and inundations. This statistical metric represents the frequency of exceedance of specific maximum flow values over a given time period, based on observed data.

The value of the probability of exceeding $p\%$ of empirical data of annual runoff values is calculated using Equation (11):

$$p = [(m - 0.3)/(n + 0.4)] \times 100\% \quad (11)$$

where m is the ordinal number of the members of the series of runoff values, located in descending order, and n is the total number of members of the series.

2.6. Climate Projections

For this study, two Representative Concentration Pathways (RCPs)—4.5 and 8.5—were applied, using outputs from five bias-corrected General Circulation Models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) within the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) framework (2019). The selected GCMs included GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M. The projections were bilinearly interpolated to a 0.5-degree resolution and bias-corrected using the WATCH ERA40 reanalysis dataset for the period 1960–1999 [57]. This bias-correction method [70] assumes the persistence of long-term trends in modelled climate variables. These climate models adequately capture the current temperature and precipitation patterns in the study region.

To analyse the impacts of climate change, the projection time series were divided into three future periods: 2011–2040, 2041–2070, and 2071–2099. These projections were compared to the historical baseline period (1984–2010) to assess future changes in hydrometeorological conditions.

3. Results and Discussion

3.1. Analysis of Observed Hydrometeorological Parameters

The Zhabay River exhibits significant seasonal and long-term variability in its flow regime. Rivers within the Yesil basin are characterized by substantial water level fluctua-

tions, with distinct high-water and low-water periods. Maximum water level rises during spring floods can be considerable, influenced by factors such as annual runoff volume, channel and floodplain characteristics, and bank structure. The annual amplitude of water level fluctuations in the region varies significantly [71].

While Russian scientists have adopted water level amplitude as the primary hazard risk indicator [72], Kazakhstan has developed its own classification system to account for the unique characteristics of its river regimes [1]. To analyse the seasonal and long-term variability of years with maximum water discharge in the Zhabay-Atbasar river basin, a difference-integral curve was constructed (Figure 5).



Figure 5. Difference-integral curve of maximum water runoff of the Zhabay-Atbasar region.

The difference-integral curve of annual runoff illustrates the time course of the accumulated difference $\sum (k_i - 1)/Cv$. The rising phase of the curve indicates a high-water period (runoff above the sample average), while the falling phase represents a low-water period (runoff below the average). The inflection points mark the boundaries between these periods. The difference-integral curve of water runoff reveals a distinct pattern: a high-water period from 1985 to 1999, followed by a low-water period from 1999 to 2014. Since 2014, the basin has experienced extreme water conditions, characterized by years of high-water content in the Zhabay River. Given the relatively short observational record, directly determining the probability of rare high-flow events is challenging. To analyse runoff fluctuations over time, probabilistic methods are applied.

The empirical probability (p) of annual maximum runoff is defined as the average number of years (expressed as a percentage of total years) in which annual runoff equals or exceeds a specified threshold.

To evaluate the impact of climate change on flooding in the Zhabay River basin, a cumulative distribution function (CDF) was constructed (Figure 6). The statistical parameters of the frequency curve include: Coefficient of Variation ($Cv = 0.96$), Coefficient of Asymmetry ($Cs = 1.9 \times Cv$), $Cs = 1.82$, Mean Annual Flow ($R_0 = 331 \text{ m}^3/\text{s}$). These are key hydrological characteristics. The coefficient of variation (Cv) quantifies the relative variability of data by comparing standard deviation to the mean. The asymmetry coefficient (Cs) indicates the degree and direction of skewness in the data distribution. According to the frequency curve, the maximum water runoff rate corresponding to a 5% probability of exceedance occurred once during the historical period. This extreme event, recorded

in 2007, reached $1150 \text{ m}^3/\text{s}$. A long-term variability assessment of river flow was conducted using field data from the Zhabay River–Atbasar City gauge. The dataset covers average annual water flow during the growing seasons (April–September) from 2000 to 2020 (Figure 7).

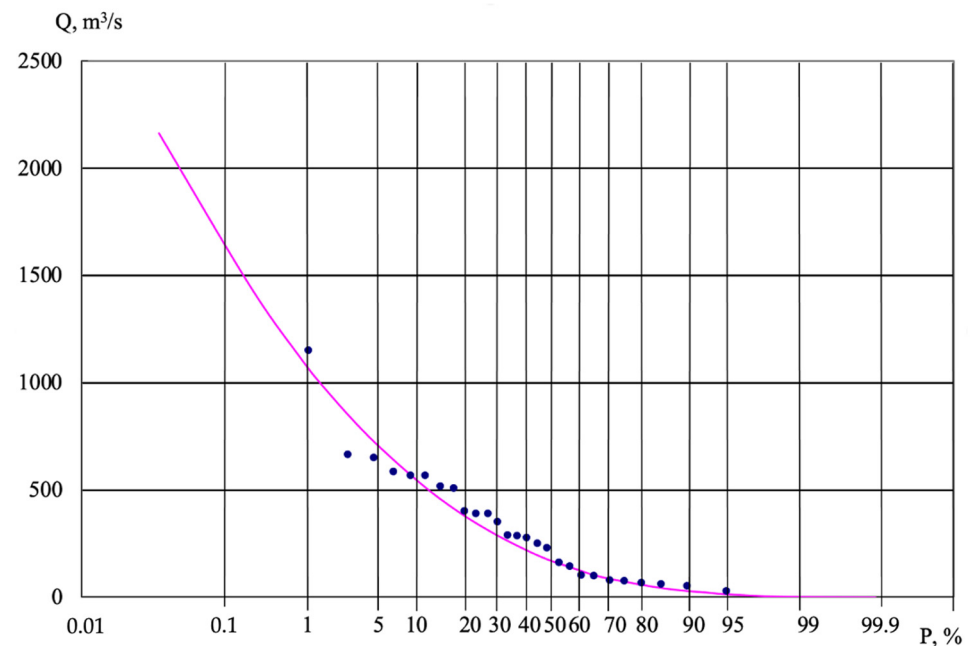


Figure 6. Cumulative distribution function for maximum water discharge for 1984–2010 in the Zhabay-Atbasar region.

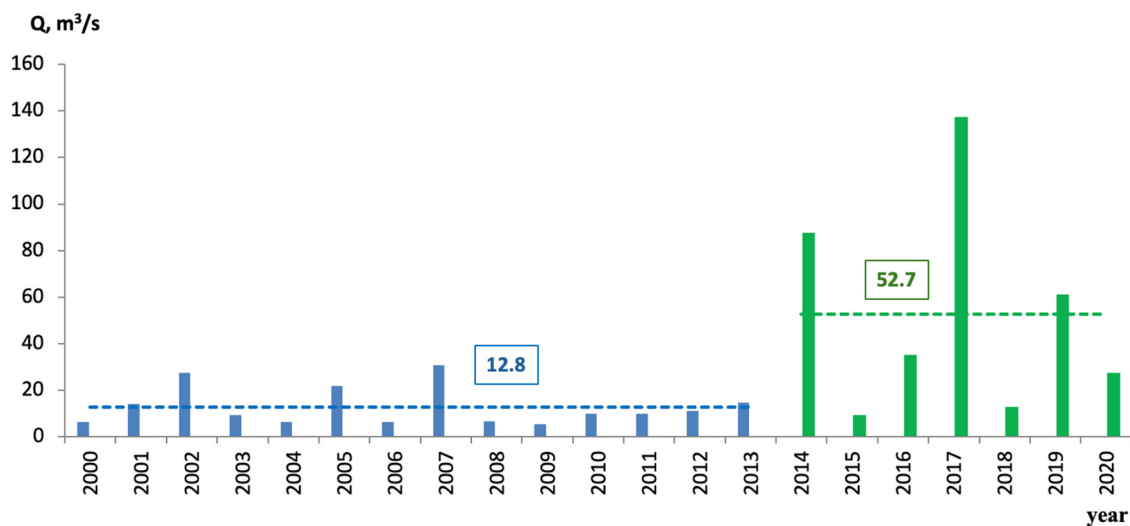


Figure 7. Average water discharge for the period April–September in the Zhabay-Atbasar region.

Figure 7 illustrates the interannual variation of average water discharge for the specified period, showing a notable increase in runoff since 2014. To analyse this trend, the interannual variation of seasonal air temperatures and precipitation at representative weather stations within the Zhabay River basin was examined (Table 1). At the initial stage, hydrometeorological observation data were checked and analysed for completeness and quality. Table 3 presents the results of the homogeneity check for each station, based on five statistical tests, along with a comparison against critical values.

Table 3. Summary of results of homogeneity test of annual mean air temperature values for selected meteorological stations.

Meteorological Station	Selected Period	By Student's Method	According to the Von Neumann Relation		By the Alexandersson Method		Buichand's Method		According to Pettitt's Method	
		<1.96	1% (1.31)	5% (1.51)	1% (11,12)	5% (8.21)	1% (1.75)	5% (1.54)	1% (233)	5% (187)
Atbasar	1980–2022	2.03		2.19		6.08		1.34		16
Balkashino	1980–2022	1.93		2.18		5.79		1.42		12
Zhaltyr	1980–2022	1.68		2.58		4.67		1.29		16
Shchuchinsk	1980–2022	1.99		2.25		5.52		1.35		0
Akkol	1980–2022	1.54		2.31		4.15		1.22		96

According to Student's *t*-test, the *t*-value for the Atbasar and Shchuchinsk meteorological stations exceeds the critical threshold of 1.96, indicating that the time series for these stations are not homogeneous. For the remaining stations, the series are homogeneous under this criterion. Using the Von Neumann ratio method, all time series were found to be homogeneous, as the N-value exceeds the significance level, meeting the methodological requirements. Similarly, Pettitt's test confirmed homogeneity across all series, as the calculated values were significantly lower than the critical values. According to the Alexandersson and Buishand tests, the meteorological station time series are homogeneous. Since only one of the five tests failed to confirm homogeneity for MS Atbasar and Shchuchinsk, the series for these stations can still be considered homogeneous.

3.2. Model Calibration and Validation

A SWIM model was configured for the study area using collected climate, hydrological, and spatial data. To ensure accurate simulation of river discharge at the gauging station, the model was calibrated and validated against daily streamflow data from 2000 to 2021. The calibration period covered 2002 to 2014, while the validation period spanned 2015 to 2021. During calibration, approximately 35 parameters were considered, with snow accumulation, snowmelt, and routing parameters identified as the most sensitive. To enhance understanding of hydrological processes, additional global climate scenario data were incorporated to simulate and generate an ensemble of runoff hydrographs. In the next research phase, the model was calibrated for the entire river basin. The model demonstrated excellent calibration performance, achieving:

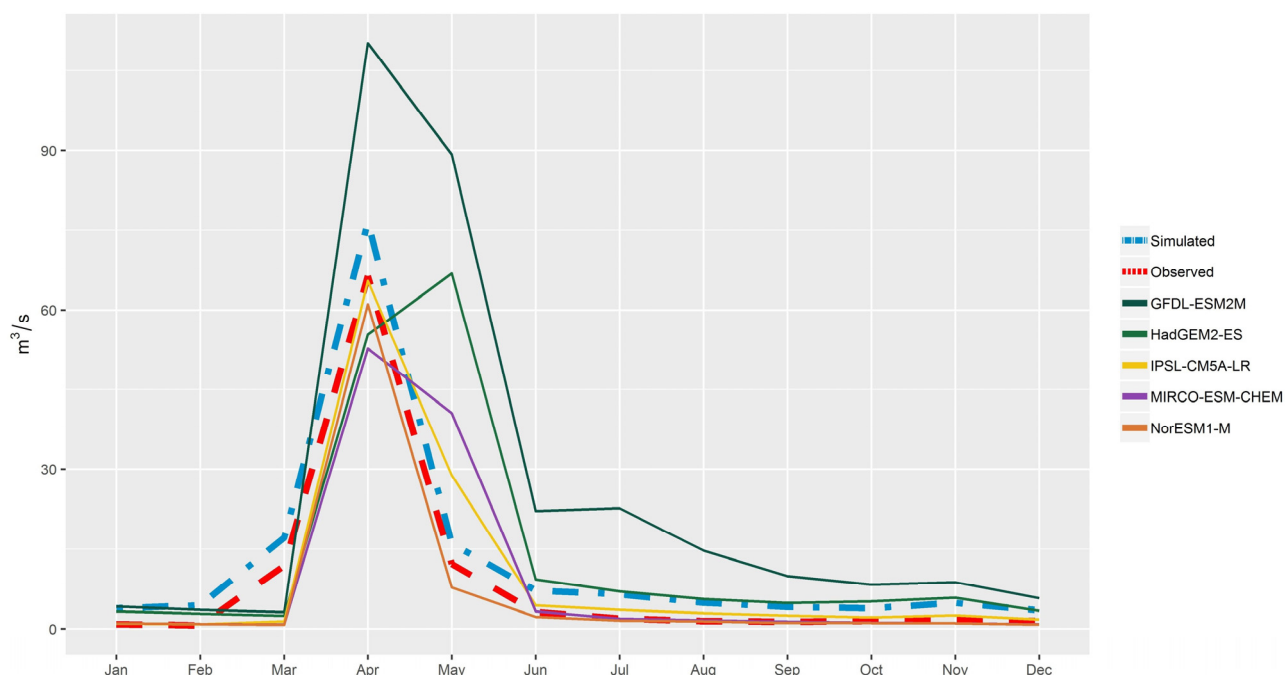
- Nash–Sutcliffe Efficiency (NSE): 0.78.
- Correlation Coefficient (R): 0.81.
- Percent Bias (PBIAS): 14.5%.
- Coefficient of Determination (R^2): 0.73.

These results indicate that the model is suitable for application under different climate scenarios [63]. The calibration parameters for the Zhabay River are presented in Table 4.

Figure 8 illustrates the distribution of observed and simulated seasonal river discharge, comparing historical simulations based on five GCMs. While most models show good agreement with the observed data, the GFDL-ESM2M model tends to overestimate river flow during the March–June period.

Table 4. Calibrated parameters of the SWIM model for Zhabay River.

Parameter	Description	Parameter Value(s)
roc	riverbed roughness coefficients	roc2 = 1.43, roc4 = 2.53
cnum	parameters of maximum soil water capacity	cnum1 = 43, cnum2 = 68, cnum3 = 91
ecal, thc	evaporation parameters	ecal = 1.03, thc = 0.96
gwq0, abf0, gwDelayDays	groundwater parameters	gwq0 = 0.2, abf0 = 0.1, gwDelayDays = 3.02
ekc0	parameters of soil erosion	ekc0 = 1
snow1	parameters of the initial moisture reserve in soils	snow1 = 0
chwc0	parameters of the riverbed and channel	chwc0 = 1
tsnfall, tmelt, smrate, gmrate	parameters of snow accumulation and snow melting	tsnfall = 0.98, tmelt = −2.91, smrate = 0.14, gmrate = 0.3
xgrad, tgrad	coefficients of change in characteristics with height	xgrad = 0.001, tgrad = −0.005
da, km2	watershed area	8530
roc	riverbed roughness coefficients	roc2 = 1.46, roc4 = 2.49
cnum	parameters of maximum soil water capacity	cnum1 = 45, cnum2 = 70, cnum3 = 93
ecal, thc	evaporation parameters	ecal = 1.03, thc = 0.96

**Figure 8.** Seasonal distribution of water runoff in the Zhabay-Atbasar region during the historical period.

Analysis of the simulated hydrographs in Figure 8 indicates that the GFDL-ESM2M model exhibits the highest sensitivity compared to the other four models. Consequently, it was selected for further flood analysis, as it has the potential to generate more extreme scenarios.

3.3. Projection of Runoff Changes According to Climate Scenarios

For this study, moderate (RCP 4.5) and high (RCP 8.5) emission scenarios were considered through the end of the 21st century. Climate projections were calculated for these scenarios up to 2099. Figure 9 illustrates the seasonal dynamics of river runoff at the Atbasar gauge station from 2010 to 2099, divided into 30-year intervals.

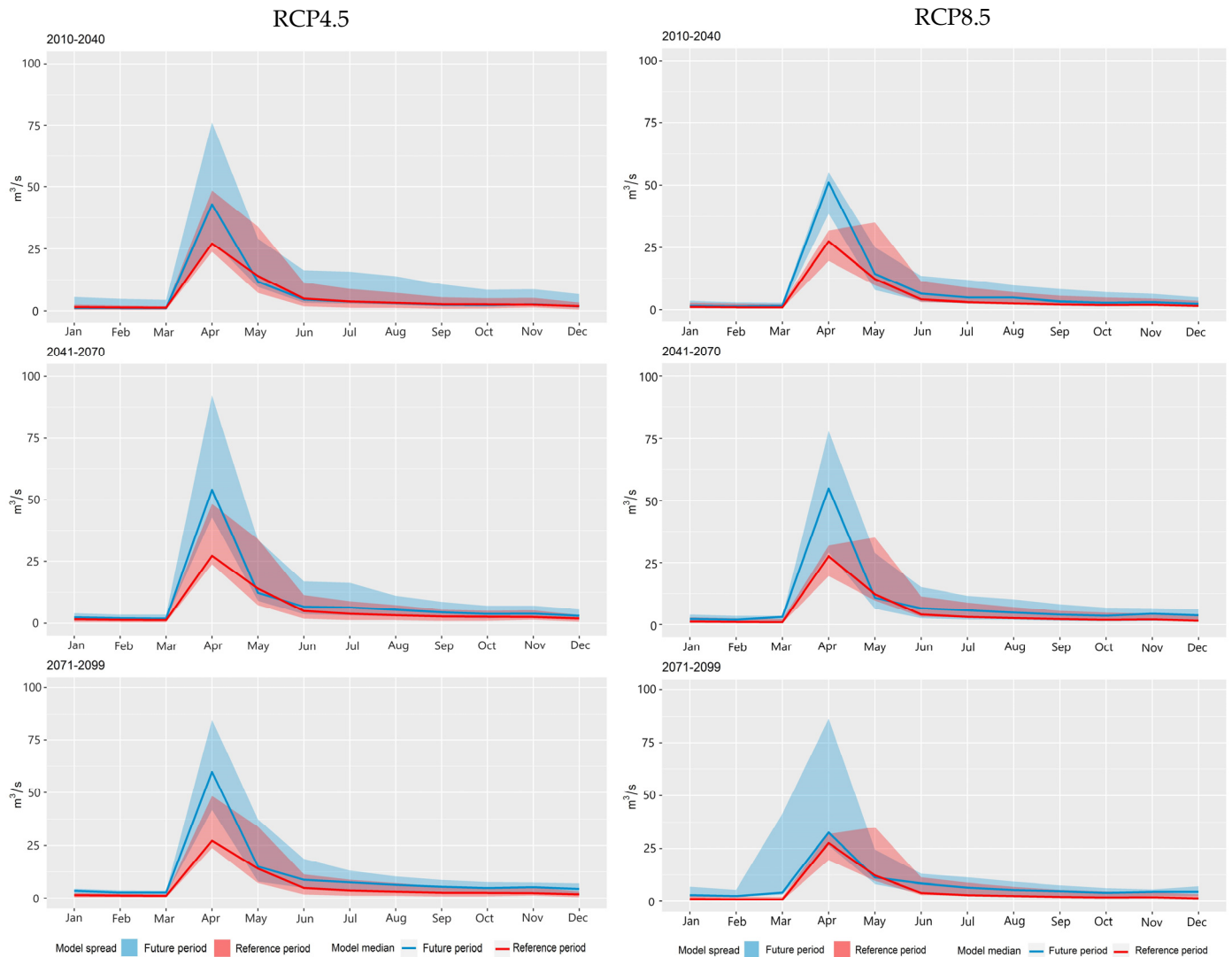


Figure 9. Seasonal dynamics of runoff at the Atbasar gauge according to the RCP 4.5 and RCP 8.5 scenarios.

Under the RCP 4.5 scenario, the peak flood volume in the Zhabay-Atbasar region is projected to increase by approximately 1.5 times between 2010 and 2040. A more significant increase is expected in April, with a twofold rise in peak flood volume from 2041 to 2070. Beyond 2071–2099, river discharge is projected to continue increasing. Although constant flooding of the riverbed is expected, the results of this scenario remain critical for water resource management planning on the Zhabay River. Under the RCP 8.5 scenario, the spring flood peak in the Zhabay-Atbasar region is projected to double between 2010 and 2040. A further twofold increase in peak flood volume is anticipated from 2041 to 2070. While river discharge is expected to approach current water level parameters from 2071 to 2099, the risk of significant peak flood events remains.

3.4. Assessment of Climate Change on Flooding Risks in the Zhabay River Basin

Frequency curves were constructed based on climate data for the GFDL-ESM2M RCP 4.5 and GFDL-ESM2M RCP 8.5 scenarios (Figure 10). Table 5 presents the main statistical parameters of the frequency analysis.

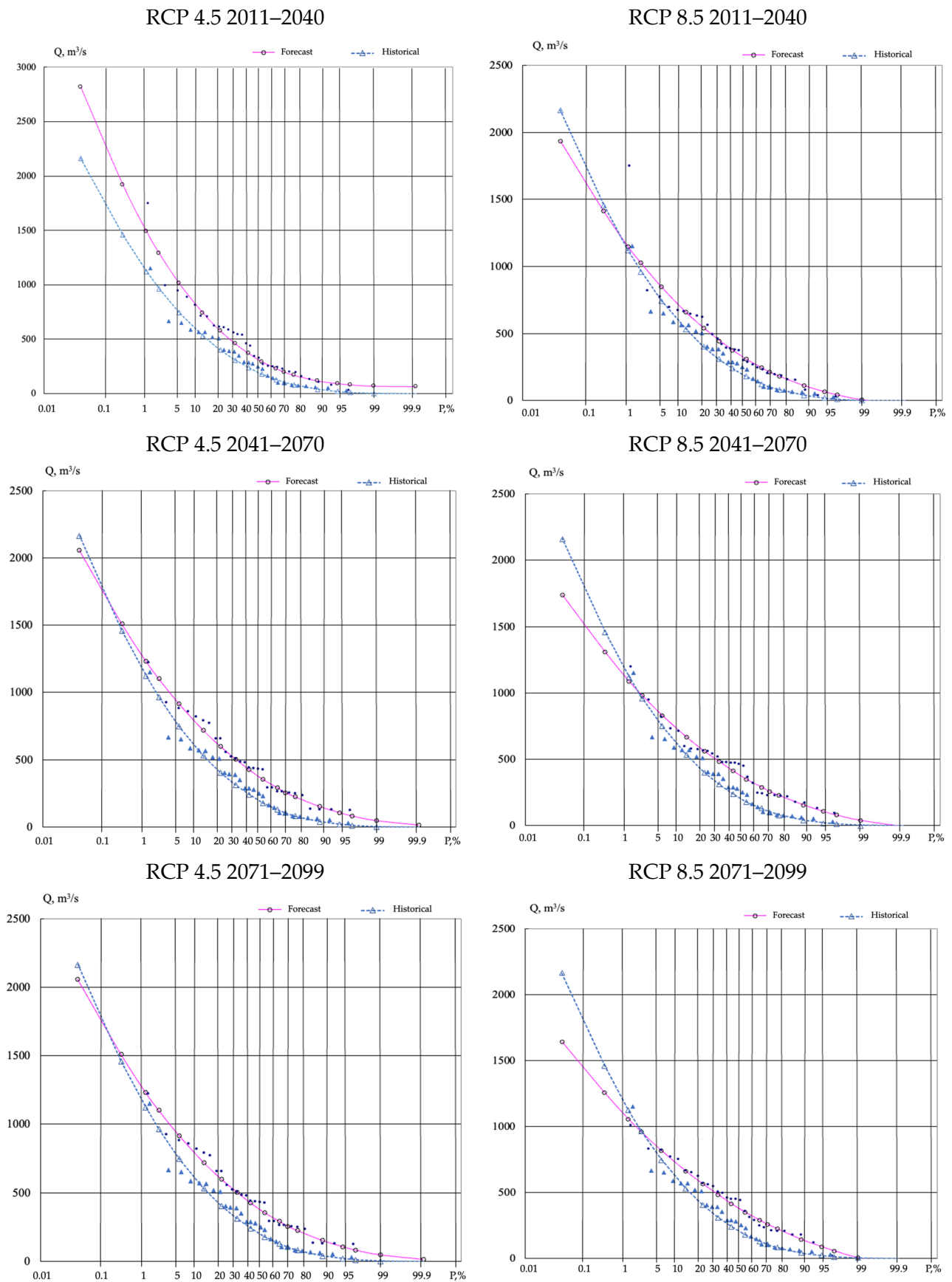


Figure 10. Cumulative distribution function for maximum water discharge from 2011 to 2099 in the Zhabay-Atbasar region according to the GFDL-ESM2M RCP 4.5 and GFDL-ESM2M RCP 8.5 scenarios.

Table 5. Statistical parameters of probability curves.

Scenarios	Periods	Cv	Cs/Cv	Cs	$Q_{Avg}, m^3/s$
RCP 4.5	2011–2040	0.83	2.40	1.99	486.9
	2041–2070	0.50	1.50	0.75	512.9
	2071–2099	0.65	1.70	1.11	489.9
RCP 8.5	2011–2040	0.70	1.80	1.26	437.3
	2041–2070	0.60	1.80	1.08	459.0
	2071–2099	0.60	1.50	0.90	451.9

The following characteristics are presented in Table 5 and Figure 10: annual mean water discharge (Q_{avg}); coefficient of variation (Cv); coefficient of asymmetry (Cs); and the ratio of asymmetry coefficient to the coefficient of variation (Cs/Cv).

The Cs/Cv ratio is a crucial metric in hydrological analysis, particularly for assessing river flow distribution patterns. This indicator allows researchers to:

- Assess the shape of the distribution: A high Cs/Cv ratio indicates significant asymmetry, suggesting the occurrence of rare but extreme runoff events. A low Cs/Cv ratio suggests a more symmetrical distribution, where extreme values have less influence.
- Classify hydrological conditions: Helps identify flow regime variations, such as low-water and high-water periods.
- Assists in determining how much the flow distribution deviates from a normal (Gaussian) distribution.
- Predict the probability of extreme events: Used in constructing flow duration curves, which are crucial for considering rare events such as floods or droughts.

The Cs/Cv ratio provides deeper insights into hydrological variability and the frequency of extreme events.

Although the projections in Table 3 do not definitively establish trends in future extreme flood events, an analysis was conducted to assess the impacts of flood extent under a worst-case scenario. Under the RCP 4.5 climate scenario, discharges with return periods between 1/100 and 1/1000 years could increase by approximately 30% in the coming decades. In 2014, a flood event of approximately 1750 m³/s was recorded in Atbasar. A 30% increase in such an event would result in a peak discharge of 2275 m³/s.

Figure 11 presents the estimated flood extents under these conditions, modelled using the FastFlood app [63] on a 40 m grid (resampled SRTM). In these scenarios, the selected river discharges near Atbasar were achieved by distributing equal portions of 50% from the two upstream tributaries. The results indicate that, in the immediate vicinity of Atbasar, particularly along its eastern boundary bordering the Zhabay River, flood extents remain nearly unchanged between the two scenarios. However, notable differences in flood extents are observed upstream and downstream of urban Atbasar, highlighting rural areas that are more vulnerable to extreme flood events. Future studies should focus on these high-risk rural areas, identifying exposed assets, and exploring potential mitigation strategies to reduce flood-related damages.

The year 2024 was characterized by an abnormally high amount of precipitation during the winter-spring period. According to the Republican State Enterprise “Kazhydromet”, snowfall in February exceeded the seasonal norm by 1.1 to 6.6 times. The combination of excessive precipitation and fluctuating air temperatures, with frequent shifts between cold and warm spells, led to the formation of extreme floods. Thaws began in March, with the snow cover accumulating a significant amount of water. In the second half of March and April, the simultaneous release of this water triggered severe flooding in the plain rivers of Kazakhstan. Hydrotechnical facilities operated under emergency conditions, struggling

to manage the high inflows. The most significant water level rises of 1.2 to 1.7 m were recorded on the Yesil River and the Zhabay River.

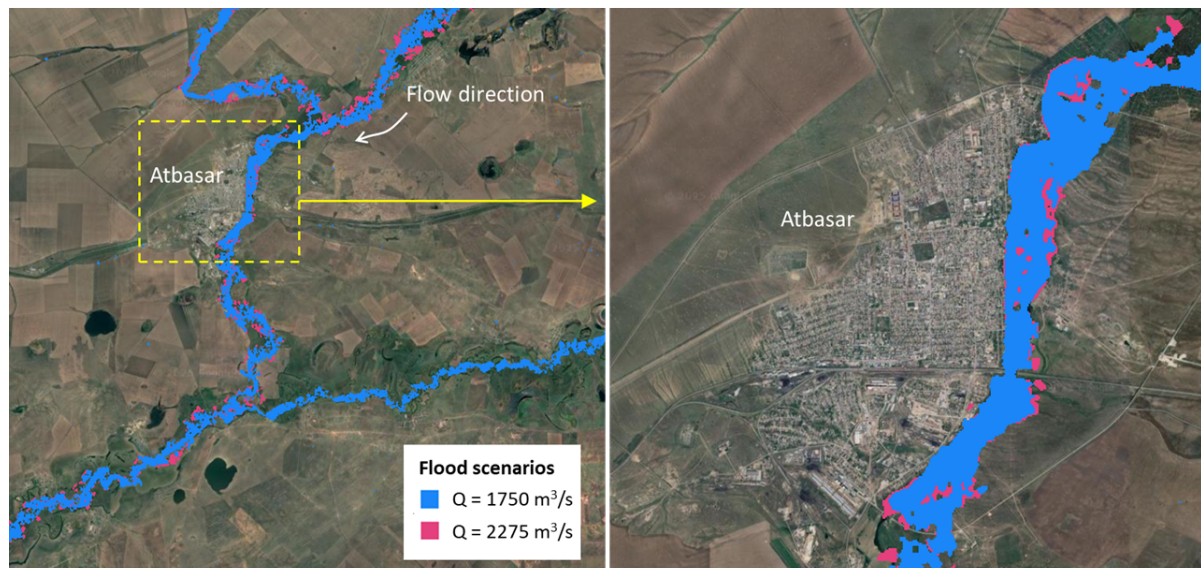


Figure 11. Flood area estimation map using the FastFlood app on a 40 m grid.

Based on our research, the cumulative distribution function (CDF) for maximum water discharge over the historical period, along with frequency curves derived from climate projections, indicates a growing number of extreme flood events:

- Between 2011 and 2040, under the GFDL-ESM2M RCP 4.5 and RCP 8.5 scenarios, the frequency of events exceeding the 5% probability threshold on the Zhabay River is projected to increase.
- Between 2071 and 2099, under the GFDL-ESM2M RCP 4.5 scenario, a significant increase in runoff is predicted, potentially leading to catastrophic floods.

A detailed analysis of water runoff availability across various climate scenarios is provided in Table 6.

Table 6. Water runoff in the Zhabay-Atbasar region for different periods and scenarios.

Scenario	Periods	Water Flow with Probability of Exceedance (%), m ³ /s					
		0.1%	1%	3%	5%	10%	25%
RCP 4.5	1984–2010	2164	1459	1122	963	747	466
	2011–2040	2818	1921	1493	1291	1016	659
	2041–2070	1582	1246	1067	982	857	667
	2071–2099	2057	1508	1232	1101	917	658
RCP 8.5	2011–2040	1935	1413	1149	1025	848	599
	2041–2070	1738	1307	1085	978	828	612
	2071–2099	1640	1255	1054	956	815	611

A probabilistic approach can be used to assess changes in hydrological conditions, particularly in relation to extreme events such as floods and spills. This method provides a general estimate of the potential impacts of climate change on these events. While the Zhabay River basin is highly susceptible to catastrophic floods, other studied basins may exhibit lower flood risks.

The SWIM hydrological model was successfully calibrated and adapted to simulate daily water runoff in the Zhabay River catchment. This enabled projections and analyses of future river discharge through 2099, using bias-corrected global climate model (GCM)

projections under two Representative Concentration Pathways (RCP 4.5 and RCP 8.5). These projections offer critical insights into the potential hydrological impacts of climate change in the region. The analysis revealed a substantial increase in spring flood peaks under both climate scenarios:

- Between 2010 and 2040, peak discharge during spring floods is projected to increase by approximately 1.8 times, from 26 to 47 m³/s.
- Between 2041 and 2070, spring flood peaks are expected to double, reaching 52 m³/s.
- From 2071 to 2099, under RCP 4.5, river discharge is projected to continue rising, emphasizing the need for long-term water resource management planning.

Conversely, under RCP 8.5, while overall river discharge may remain closer to current levels, the risk of extreme peak floods persists, posing a potential threat of catastrophic flood events. This underscores the Zhabay River's vulnerability to climate-induced variability, particularly in the context of extreme weather events.

The seasonal and quantitative distribution of river discharge is expected to undergo significant changes throughout the 21st century:

- 2010–2040: Snowmelt will be the primary driver of surface runoff, amplifying flood peaks by up to 1.5 times.
- Post-2041: Increasing winter precipitation combined with rising spring rainfall is expected to further intensify spring floods, with peak discharges reaching 2 to 2.5 times current levels.
- 2071–2099: Rising air temperatures will likely cause earlier snowmelt, shifting the maximum surface runoff earlier in the year. This shift is expected to shorten the snow accumulation period, reduce soil freezing, and ultimately decrease river discharge compared to the 2041–2070 period.

Under the GFDL-ESM2M RCP 4.5 scenario, extreme flood events on the Zhabay River are projected to become more frequent:

- 2011–2040: A 1% probability (100-year recurrence interval) flood is expected to reach 2000 m³/s, a 500 m³/s increase over the historical maximum (1984–2010).
- 2011–2040 & 2071–2099: A 5% probability (20-year recurrence interval) flood is expected to exceed the historical maximum by 200 m³/s.
- RCP 8.5 scenario: No significant increase in extreme flood events exceeding the 1.5% probability threshold is projected.

This research highlights the growing challenges posed by climate change and underscores the critical need for accurate water resource assessments. The use of hydrological models, such as SWIM, provides a valuable tool for daily water flow forecasting, which is essential for effective water resource planning and management. The findings of this study are highly relevant to decision-makers managing the Zhabay River catchment and other climate-sensitive river basins. The successful application of SWIM in this research also demonstrates its potential for adaptation to other river basins in Kazakhstan and beyond. As the impacts of climate change become increasingly apparent, the ability to predict river discharge and flood events will play a key role in sustainable water management and long-term infrastructure planning. This approach can be further integrated with existing hydrodynamic and hydraulic models, creating a comprehensive framework for flood risk mitigation and the development of resilient water management strategies.

4. Conclusions

Modelling results indicate that climate change is increasing the intensity and frequency of extreme precipitation events in the Zhabay River basin, leading to a higher risk of flooding, particularly during spring and summer, when runoff peaks. As a result of these

climatic changes, seasonal runoff patterns are expected to redistribute, with increased winter runoff. The flood risk is not uniform across the basin—the greatest vulnerability is observed in lowland areas near the river channel, where runoff accumulation leads to significant flooding. This study aligns with global trends in assessing hydrological changes associated with climate change. The findings indicate an increase in peak flows in the Zhabay River basin, consistent with results for other Kazakh rivers, such as the Syr Darya and Yesil basins [3,4]. Similar studies for other plain rivers in Kazakhstan, including the Tobol and Ertis rivers, have also reported an increase in flood frequency and extreme flow events. Earlier studies, such as those by Ospanova M.S., focused on flood risk assessment and mitigation in the Yesil River basin, while Makhmudova L.K. examined flood-prone zones. However, previous research did not include long-term scenario-based forecasts of Zhabay River discharge up to 2099, making this study a novel contribution to hydrological research in the region.

Beyond climate change, intensive land use and modifications to the natural water balance—such as the construction of dams and reservoirs—further increase flood susceptibility by reducing the basin's ability to regulate runoff naturally. The application of climate change scenarios in hydrological models allows for a more comprehensive assessment of both current and future flood risks. A major limitation of this study is the scarcity of hydrological data in Kazakhstan. The density of hydrometeorological stations remains below international standards, limiting the precision of hydrological assessments. Future research should integrate additional factors influencing flow formation, including ecosystem changes, anthropogenic impacts, and possible adaptation strategies.

To effectively manage flood risks, it is essential to develop and implement localized early warning systems that enable a prompt response to impending flood threats. Strengthening the monitoring of hydrometeorological conditions through advanced technologies, including remote sensing, will enhance the accuracy and timeliness of flood forecasts, improving overall preparedness. Additionally, implementing adaptation measures, such as creating buffer zones, regulating development in high-risk areas, and increasing the capacity of water bodies to manage excess runoff, will play a crucial role in mitigating flood impacts. This study provides a foundation for further research into climate adaptation and sustainable water resource management in the Zhabay River basin. The findings emphasize the need for an integrated, multidisciplinary approach to mitigating flood impacts in a changing climate. Future resilience strategies must incorporate both structural and non-structural interventions to address the increasing frequency and severity of flood events.

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