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The Impact of Climate Change on Hydrological Regime of the Transboundary River Shu Basin (Kazakhstan–Kyrgyzstan): Forecast for 2050

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Abstract: The impact of regional climate change on the runoff and the regime of glacier- and snow-fed rivers in the transboundary river Shu basin between Kazakhstan and Kyrgyzstan is investigated. This study covered three of the most representative rivers of the Shu basin. It was based on the weather and gauging stations' observation data in the river Shu basin — the northern Tien Shan. Based on the trend analysis, an increase in the average annual temperature and river discharge was identified within the observation period as a whole, and for the separate compared periods. Furthermore, the mean annual flow projections were made based on the methodology of the retrospective analysis of runoff and the rate of river flow increase for the observation period, and further extrapolation of data for the forecast period. According to the analysis, the mean annual flow for the considered rivers will be decreased by 25 to 30% on average by 2050. These findings are necessary for elaborating adaptation measures in water allocation for freshwater supply, irrigation and hydropower within this transboundary river.

Keywords: climate change; glacier-and snow-fed rivers; hydrological regime; forecast

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1. Introduction

Due to the processes of global climate change that have been taking place throughout the 20th and into the 21st century, the concept of long-term flow fluctuations underlying the methodology for the calculation of the main hydrological characteristics necessary for the design and construction of various structures and the management of water resources, including the water allocation of transboundary rivers, requires a review based on comprehensive analysis and adjustment. Scientists and specialists' opinions on the inevitability of further climate change are unanimous, although the conclusions on its intensity and scale are ambiguous worldwide and in the region [1–3].

Climate change has always drawn the attention of scientists, but in the 1970s it became a global issue. It was from this decade onward that the signs of climate change began to manifest themselves more clearly. These changes were exhibited in the form of extreme weather events such as frequent droughts, catastrophic floods, and an increase in the inter-annual and inter-seasonal fluctuations of amplitudes of the air temperature, with a general tendency to increase both seasonal and annual average monthly temperatures.

The results, summarised in the Intergovernmental Group of Experts report, showed that the global average annual air temperature has increased by 0.3–0.60 °C over the past century [4]. The trend of climate warming persists today, and especially significant warming occurred in the current century. It is assumed that by the middle or the end of the present century, the concentration of CO_2 in the atmosphere will be doubled. Carbon dioxide controls the amount of water vapour in the atmosphere and thus the size of the greenhouse effect. The resultant increase rate of the average annual, decadal temperature will range between 0.2 and 0.4 °C (2–4 °C per century).

Detecting variability and trends in river streamflow time series are vital for the appropriate management and planning of water resources. It diminishes the risks and detrimental effects associated with wrongfully assuming stationarity in hydrologic design. The Mann-Kendall test and its modification for streamflow trend analysis in a South American river was employed [5].

Understanding the spatial and temporal variability of streamflow and its relationship with climate change in a region can enhance our hydrological and ecological knowledge and improve forecasting, and reducing the impact of extreme events, including floods and drought on human activities. Climate and hydrological data often contain inter- and intra-annual variations that must be considered when studying short- and long-term changes within a region. The Least-Squares Wavelet software (LSWAVE) was applied to estimate the trend and seasonal components of sixty-year-long climate and discharge time series and to study the impact of climate change on streamflow over time in a Canadian river [6]. The wavelet spectral analysis for unevenly sampled time series was proposed in the northwestern Mediterranean basin [7]. To analyse the potential impact of climate change on the streamflow in a river basin located in the northern latitude of Nepal, the Soil and Water Assessment Tool (SWAT) hydrological model was used [8].

Climate change means a gradual variability of the main average parameters within a long-term period, such as temperature, precipitation, and evaporation [9]. Climate change is evident and relevant now and will remain so in the future, both globally and regionally, notably in Kazakhstan and Kyrgyzstan [10–15].

Significant declines were identified in annual glacier runoff over the twenty-first century for Central Asia [16]. Climate-driven changes in glacier-fed streamflow regimes have direct implications on freshwater supply, irrigation and hydropower potential. These changes in glaciers and runoff in the Tien Shan mountains (Central Asia) have been addressed in previous studies [17–19]. Over the past decade, climate change has influenced terrestrial water storage by affecting glaciers and snow cover change in Central Asia's mountainous regions [20]. Knowing the glacier and snow cover fluctuations in these regions is essential for their importance to the water supply [21–23]. Although the impacts of climate change on glaciation and runoff have been addressed in previous works undertaken in the Tien Shan mountains (with their status as "water tower" of Central Asia), a coherent regional and mostly local perspective of these findings has not been presented until now. Reliable information about current and future glaciation and runoff is crucial for water allocation, a complicated task even at a local level. The impact of glacier shrinkage on water availability remains poorly understood [24]. With a changed annual area of 0.36 to 0.76%, glaciers retreat particularly fast in the northern Tien Shan, thus causing concern about future water security in the densely populated regions of these countries. These transboundary regions strongly depend on glacial meltwater for freshwater supply, irrigation and hydropower production. Therefore, efficient adaptation strategies should consider the interests of each state based on interstate cooperation [25].

The countries of Central Asia, located in arid zones, can be attributed to the region most susceptible to climate change. Despite the peculiarities of each country's territorial and climatic specifics and economic development, they have common environmental and socio-economic problems [26].

This study involved climatic change analysis made at the local level, encompassing the northern Tien Shan mountains focusing on the river Shu transboundary basin. The aim was to assess climate change and its impact on river flow availability in the runoff generation zone in the river Shu basin between Kazakhstan and Kyrgyzstan over a long-term period, to identify change trends to forecast water availability up until 2050. It must be stressed that irrigation is the primary economic sector in these countries [27–30].

The tasks were to: (1) assess the dynamics of the changes in temperature and precipitation according to the characteristic weather stations (alpine, foothill, and plain) of the river Shu basin over a long-term period; (2) assess the dynamics of the changes in water availability in the main river sections recorded over a long-term period; (3) identify trends in the temperature and river flow; and (4) provide a forecast of river flow, taking into account the impact of climate change.

Herein, the authors present their results derived from the analysis of the changes observed in the main climatic parameters such as air temperature and precipitation (which are the main factors in the production of runoff) for the period of instrumental observations, and, as a consequence, the dynamics of the river Shu and its main tributaries flow regime.

2. The Study Area

The river Shu basin is located within two states. It occupies the northern part of Kyrgyzstan and the southern part of Kazakhstan and is a transboundary waterway (Figure 1). The river Shu is formed as a result of the confluence of the Kochkor and Djuanaryk rivers. It has a length of 1186 km, of which 850 km are in the territory of Kazakhstan. The river runs 210 km along the border between Kazakhstan and Kyrgyzstan, and only a section of 126 km flows through the part of Kyrgyzstan [31].

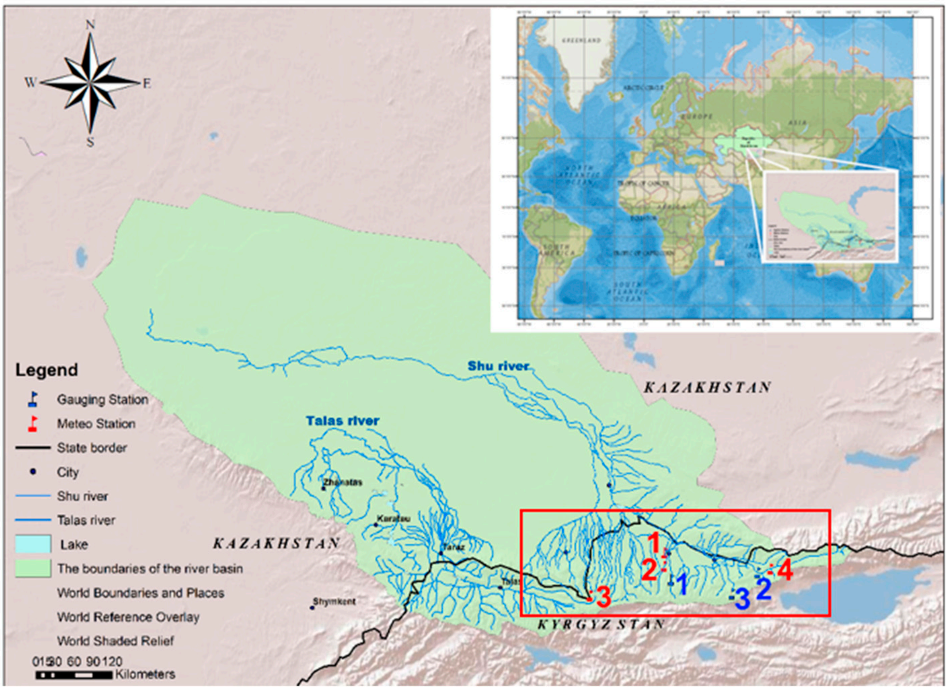

Figure 1. A map of the river Shu drainage basin and the study area.

The total drainage basin area exceeds 67,500 km^2, of which about 43% is located in Kyrgyzstan (Shu oblast) and 57% in Kazakhstan (Zhambyl oblast). At the river Shu headwaters, the runoff zone is almost entirely situated in Kyrgyzstan, as 3.84 km^3/annum or 97% of the river runoff pertains to Kyrgyzstan, and only 0.11 km^3/annum, or 3%, to Kazakhstan. The river Shu is a sinking river (so-called "Karasu" type), as it disappears in an arid and flat area in Kazakhstan; and this part is not considered in the study. In Kyrgyzstan, the river Shu basin occupies the northern part surrounded by high Tien Shan ridges, accommodating significant glaciation in the runoff generation central zone.

The climatic conditions of the river Shu basin are determined by its geographical location in the middle latitudes, in the centre of the Eurasian continent, surrounded by vast deserts and complex alpine terrain. Thus, the climate is characterised by a scarcity of precipitation, dry air, high solar radiation, and low cloud cover. All climate characteristics change, but most significantly by the zones of elevation [32,33]. One of the climate negative factors is its dryness (aridity), with less precipitation especially in the valley or the most developed area, and extensive evaporation. As a result, agricultural development in midland and lowland is possible only with artificial irrigation. For this reason, climate change that impacts the streamflow timing and amounts will cause an increase in irrigation water, which will negatively impact the region's sustainability. The list of weather stations located in the Study area is presented in Table 1.

Table 1. Weather stations located in the river Shu headwaters (the numbers in the table correspond to those in Figure 1).

	Weather Station	Elevation m.a.s.l	Zone	Observation Period
1	Bishkek	756	Plain	1932–2017
2	Baytik	1579	Foothill	1914–2017
3	Tyuya-Ashu	3120	Alpine	1959–2017
4	Shabdan	1532	Foothill	1936–2017

The river Shu's tributaries are located in the most elevated mountainous areas (above 3000 m), with natural moisture storage in snowfields, glaciers, and seasonal snow [14,34,35]. The list of gauging stations located in the Study area is presented in Table 2. The river Shu basin primary water balance components within Kyrgyzstan are given in Table 3 [36].

Table 2. Gauging stations located in the river Shu headwaters (the numbers in the table correspond to those given in Figure 1).

	River and Tributaries	Gauging Station	Catchment Area, km^2	Mean Elevation m.a.s.l.	Channel Slope %	Glacier Coverage %	Indicator δ	Observation Period
1	Shu	Kochkorka	5370	2840	15	1.0	1.13	1937–2017
2	Chon-Kemin	Outlet	1890	3010	19	6.0	1.70	1932–2017
3	Ala-Archa	Outlet	233	3290	69	17.0	2.24	1928–2017

Table 3. Basic water balance components of the river Shu basin within the area of Kyrgyzstan.

Drainage Area, km^2	Mean Elevation, m.a.s.l	Air Temperature, °C	Precipitation, mm	Evaporation, mm	Runoff mm	Specific Discharge, L/s·km^2
22,300	2166	2.45	552	364	188	5.73

The indicator δ that defines the type of river feeding or regime is the runoff volume ratio for July–August to the runoff volume for March-June [35]. This indicator is directly and closely dependent on the elevation of the catchment. It is taken as a basis for the classification of rivers by type of a dominant supply source: Glacier–snow, snow–glacier, snow, and snow–rain melting conditions. Most streams in the basin have a glacial–snow supply source in the total runoff (δ > 1.0). High water levels in these rivers are observed in May–June and end in September–October, lasting some 170–180 days. The glacier runoff share is insignificant or completely absent due to minor glaciation areas (Kyzyl-Suu, Kara-Balta, and Dzhelamysh). In the intra-annual distribution of runoff, the highest percentage falls in the summer months – from June to September (50 to 58% of the total).

3. Materials and Methods

This assessment builds up and supplements past studies in the river Shu basin [37–39]. In this study, the meteorological and hydrological data were derived from different sources: the Agency for Hydrometeorology, the State Water Resources Agency under the Government of Kyrgyzstan, as well as from various studies and reports describing the use and projection of the water resources in the river Shu basin [33,40].

The assessment of the impact of climate change was conducted based on the employment of the following data and analysis:

- Air temperature and precipitation at weather stations.
- Analysis of the temperature increase dynamics and the forecast for the period up until 2050.
- The hydrological regime and river runoff response to climate warming.

To analyse the changes in the basic climatic parameters generating the stream runoff (air temperature and precipitation), the methodology applied in this study included the residual mass curve, as well as analysis of the changes in trends and the rate of their parameters during the period of observation at the weather stations of the river Shu basin [35,41].

The residual mass curve (i.e., a graph of the cumulative departures from a given reference such as the arithmetic mean versus the time or date) method was used to detect likely trends or cycles in the time series of annual temperature and precipitation and streamflow [42]. The hydrological literature can provide more details on the residual mass curve [43,44].

To construct the residual mass curve, the ratio K was defined by the following formula:

$$K_i = Q_i / Q_{avg} \quad (1)$$

Q_i is the value of a variable of a particular year in the recorded period (e.g., mean annual flow) and Q_{avg} is the average value of the series containing n years.

$$Q_{avg} = \left(\sum_{i=1}^{n} Q_i \right) / n \quad (2)$$

when $Q_i = Q_{avg}$, then $K = 1$. The residual mass curve represents a total sum of the ratios K deviations from the mean long-term value of the series at the end of each Q_i year ($K_i - 1$).

$$\sum_{i=1}^{t} (K_i - 1) = f\ (t) \quad (3)$$

The summation over the annual time interval (t) provides either the upward or downward slope in the curve, meaning the positive or negative phase to the horizontal line, respectively.

Before proceeding with the trend analysis of variables, their time series underwent normality tests. Most of these series followed a normal distribution, and consequently there was no need to apply a nonparametric test (e.g., the Mann–Kendall trend test). Therefore, a simple linear regression was run instead. As usually, the significance level was set to $p < 0.05$.

This study analysed the main meteorological variables (i.e., air temperature and precipitation) based on the data collected at the river Shu basin weather stations located at different elevations with long-term records (Table 1). In order to establish in what period the most significant temperature changes began and to link this with changes in river runoff intensive melting of glaciers, the entire observation period was divided into separate periods. As a result, there were two reference periods when an apparent increase in air temperature started (1972 and 2001). It was done by analysing the time series.

Trend analysis of the mean annual discharge was conducted for the three most distinct streams: the river Shu at Kochkorka, and its tributaries, namely Chon-Kemin and Ala-Archa (Table 2).

The hydrological forecasting methodology employed in this study (i.e., forecast of the mean annual river flow) was based on the analysis of the relationship between the previous and subsequent hydrometeorological characteristics that determine the development of hydrological processes under specific physiographic conditions [45,46].

Considering a relatively long forecasting period (i.e., 33 years), the extrapolation method in the mean annual flow for the entire observation period was applied, provided that this trend continued by this period [32]. Therefore, the water discharge increase rate observed for 2001–2017 was adopted in the computation based on extrapolation until the projected year 2050. An alternative way to assess the projection and changes in meteorological factors and streamflow, including water yield, is to use specific climate models under different emission scenarios [8].

4. Results and Discussion

4.1. Regional Climate Change

4.1.1. Air Temperature

The trend analysis of the average annual temperature at the weather stations for the period of parallel observations (1959–2017) demonstrated an unambiguously positive tendency, with an increase of 1–2 °C on average (Figure 2). The summary of regression analysis is given in Table 4.

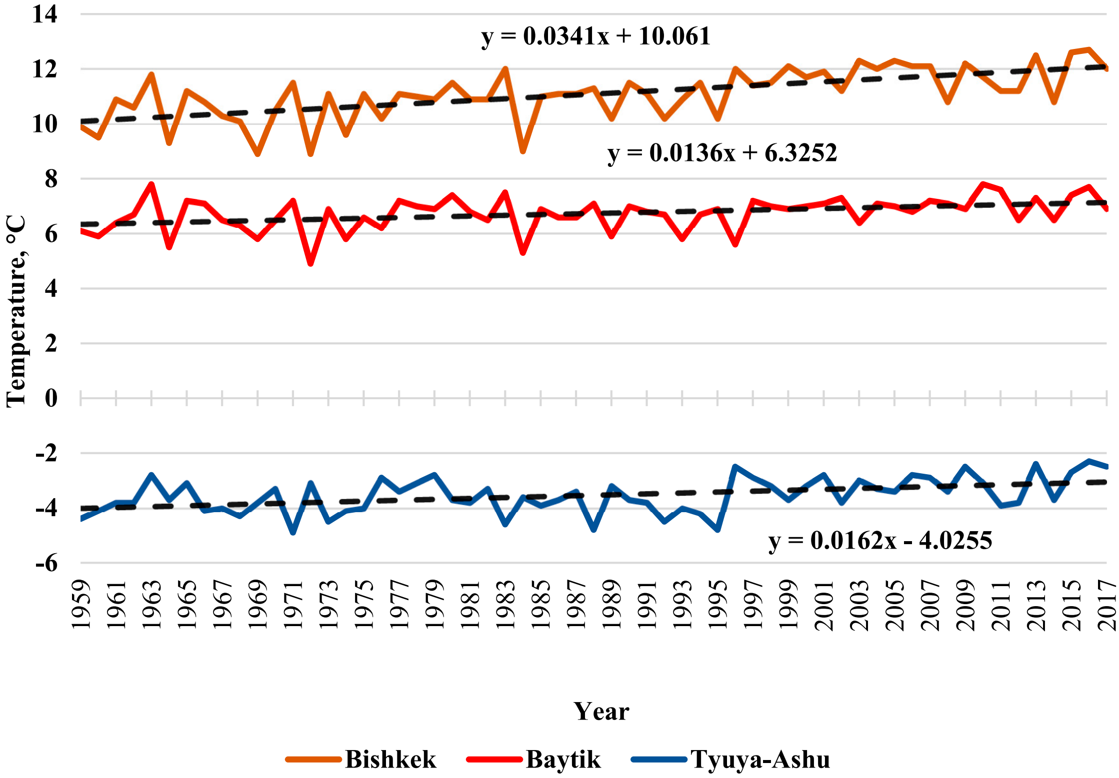

Figure 2. Average annual temperature trends based on the data of the Bishkek, Baytik, and Tyuya-Ashu weather stations (WS) for the period of parallel observations of 1959 −2017.

Table 4. Summary of regression analysis.

Weather Stations	R Squared	Observations	Standard Error	Intercept	X Variable	F	Significance F	*t* Stat	*p*-Value
Bishkek	0.40	59	0.72	10.06	0.03	38.2	ca 0	6.18	ca 0
Baytik	0.14	59	0.57	6.32	0.01	9.6	0.003	3.10	0.003
Tyuya–Ashu	0.19	59	0.59	−4.03	0.02	13.1	0.0006	3.62	0.0006

The increase in temperature over the 59 years amounted to 1.90, 0.60, and 1.0 °C for Bishkek, Baytik, and Tyuya-Ashu weather stations (WS), respectively, while the increase rate varied in the interval from 0.01 to 0.030 °C/year. In contrast, the average annual temperature trend for the entire observation period (i.e., 1914–2017, 103 years) showed a temperature increase of 0.9 °C (increase rate is 0.01 °C/year) for Baytik WS.

The analysis of trends by periods shows that the increase in temperature started after 1972, and the most significant in the period after 2000, i.e., in 2001–2017 (Figure 3).

To compare and analyse the tendency of temperature changes over a more extended period, we used data from the Baytik WS (record length of 103 years). This period was divided into ten years, for which the average temperature was calculated and a graph of temperature changes by decades was plotted (Figure 4). The minimum value of the average temperature was noted in the decade 1915–1924, the maximum—2005–2017, with a difference of 1.10 °C. Thus, the trend of climate warming has persisted and become more positive since 2000. The summary of regression analysis is given in Table 5.

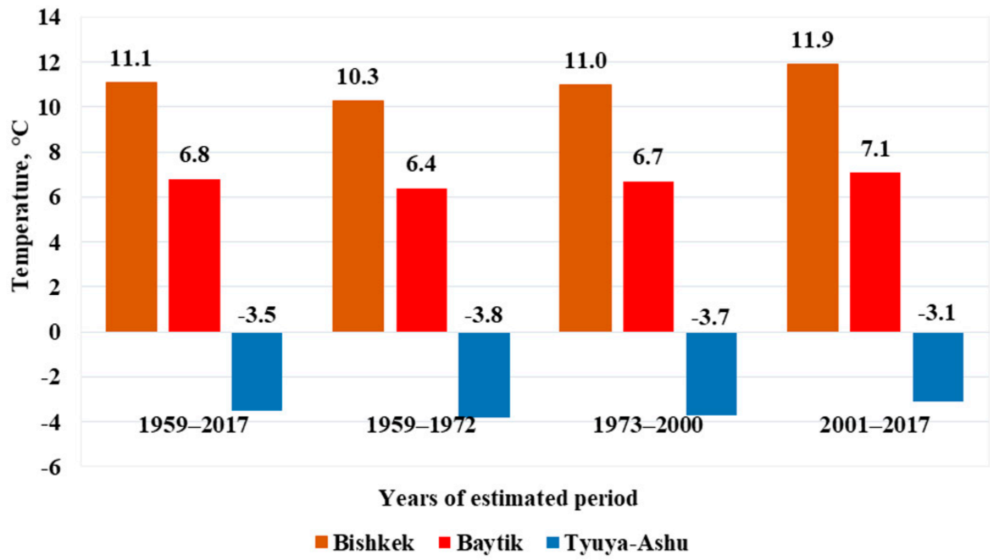

Figure 3. Mean annual temperature for the compared periods of the Bishkek, Baytik, and Tyuya-Ashu WS.

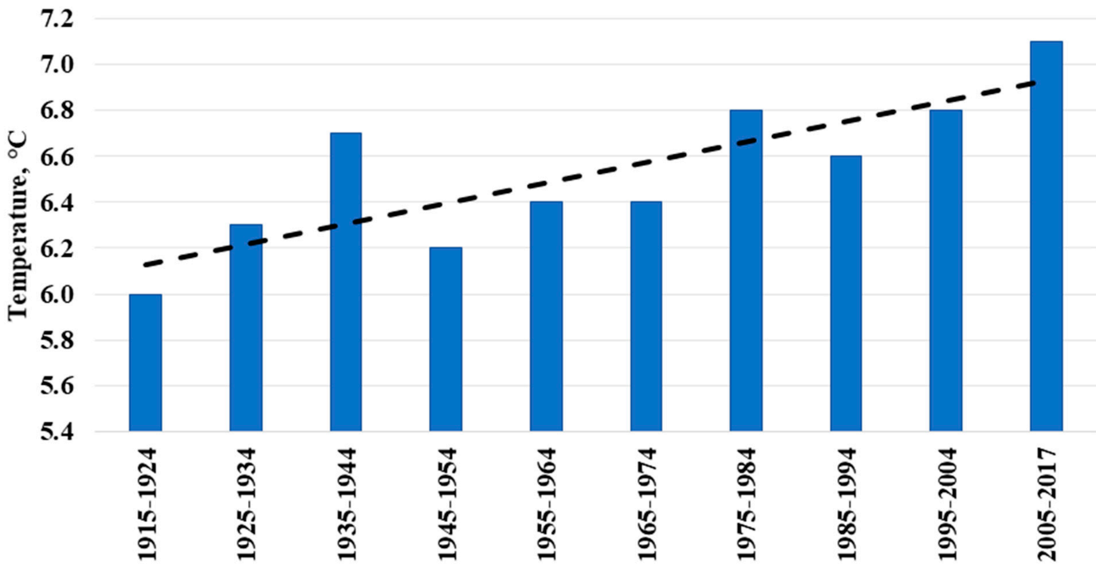

Figure 4. Decadal average annual temperature, Baytik WS.

Table 5. Summary of regression analysis, Baytik WS.

Weather Station	R Squared	Observations	Standard Error	Intercept	X Variable	F	Significance F	*t* Stat	*p*-Value
Baytik	0.67	10	0.2	6.04	0.089	16.06	0.004	4.01	0.004

According to the data of Bishkek WS, (plain zone), the increase in average monthly temperature throughout all months is positive and in the range of 0.1–2.4 °C, which is higher than that of the previous period, from 0.1 (May) to 2.4 °C (November). Baytik WS (foothill zone) data showed that October, February, and March became somewhat colder (by 0.1, 0.2, and 0.4 °C, respectively). However, in the remaining months there was an increase in air temperature, from 0.1 to 1.5 °C.

It was noted that the increase in the average annual temperature was more significant in the valley part of the catchment, —by 0.7 °C, whereas in the high mountain zone by 0.3 °C. In the Tyuya-Ashu weather station, a slight decrease in temperature was noted in January – March by 0.3–0.4 °C. In all other months, an increase by 0.1–1.0 °C was recorded.

4.1.2. Precipitation

The annual amount of precipitation for the observation periods did not change significantly (Table 6). However, their differences varied from −7.0 to +51mm (−1.2% to +11.1%), an average of 22.2 mm (4.6%) in 1973–2017. The most significant increase in precipitation, from 13 to 83 mm (2.9% to 17%) with an average of 40 mm (6.9%) (except for Baytik), occurred over the last 17 years (2001–2017).

Table 6. Annual precipitation for the different estimated periods.

Estimated Period, Years	Weather Station			
	Bishkek	Baytik	Shabdan	Tyuya-Ashu (South)
1932–1972	405	567	434	789
1932–2017	429	563	447	793
1973–2017	456	560	457	797
2001–2017	488	566	447	854

4.1.3. Analysis of Temperature Increase Rate and Forecast for 2050

The essence of forecasting is to pre-calculate a particular climate element (in this case, temperature) with various lead times and the degree of accuracy [42,47]. Table 7 shows the results of the average annual temperature, the rate of its increase in different periods, and the projection for 2050. The temperature increase rate observed in 2001-2017 was employed in the computation. This procedure is a commonly known technique of making predictions for the future by using historical data as inputs and analysing trends [45,46]. Therefore, it is a key assumption for this study. On the other hand, short-term records can result in higher uncertainties when making such a prediction.

Table 7. Average annual temperature and forecast up to 2050 based on the data of the WS.

Estimated Period, Years	Number of Years	Average T, °C	Difference of T, °C	T Increase Rate °C/annum	Projection 2050 Increase/T °C	
			Bishkek WS			
1959–2017	59	11.1				
1959–1972	14	10.3	−0.8	−0.057		
1973–2000	28	11.0	0.7	0.025		
2001–2017	17	11.9	0.9	0.053		
Projection 2018–2050	33	13.6			1.75	13.6
			Baytik WS			
1959–2017	59	6.8				
1959–1972	14	6.4	−0.4	−0.029		
1973–2000	28	6.7	0.3	0.011		
2001–2017	17	7.1	0.4	0.024		
Projection 2018–2050	33	7.9			0.8	7.9
			Tyuya-Ashu WS			
1959–2017	59	−3.5				
1959–1972	14	−3.8	−0.3	−0.021		
1973–2000	28	−3.7	0.1	0.004		
2001–2017	17	−3.1	0.6	0.035		
Projection 2018–2050	33	−2.5			0.6	−2.5

According to this forecast, the average annual temperature increase rate will not be so significant as the climatic scenarios under the UNDP framework convention. According to Kyrgyzstan's Third National Communication report, in terms of the 100 years [48], the average annual temperature within Kyrgyzstan's whole territory increased by 1.60 °C (in the range of 0.6–2.40 °C). It was significantly higher than the global warming of 0.60 °C. The maximum and minimum warming values were observed in winter (2.60 °C) and summer (1.20 °C), respectively. The temperature increase demonstrated different patterns depending on the climatic areas and high-altitude zones. Precipitation throughout the country simultaneously showed a slight increase of 23 mm or 6%.

The change in annual precipitation for both scenarios (A2-ASF and B2-MESSAGE) was assumed to be insignificant [12,48]. However, for the northern part of the country, a slight increase in precipitation was expected (by 1.3–2.1% relative to the base period until 2000). Our study shows that the temperature increase will be within the range of 0.6–1.6 °C, depending on the elevation and geographical location of weather stations.

4.2. Hydrological Regime and River Runoff Response to Climate Warming

According to the hydrograph shape, the rivers refer to the Tien Shan type [34], having floods in the warm season and low water in the cold period (Figure 5).

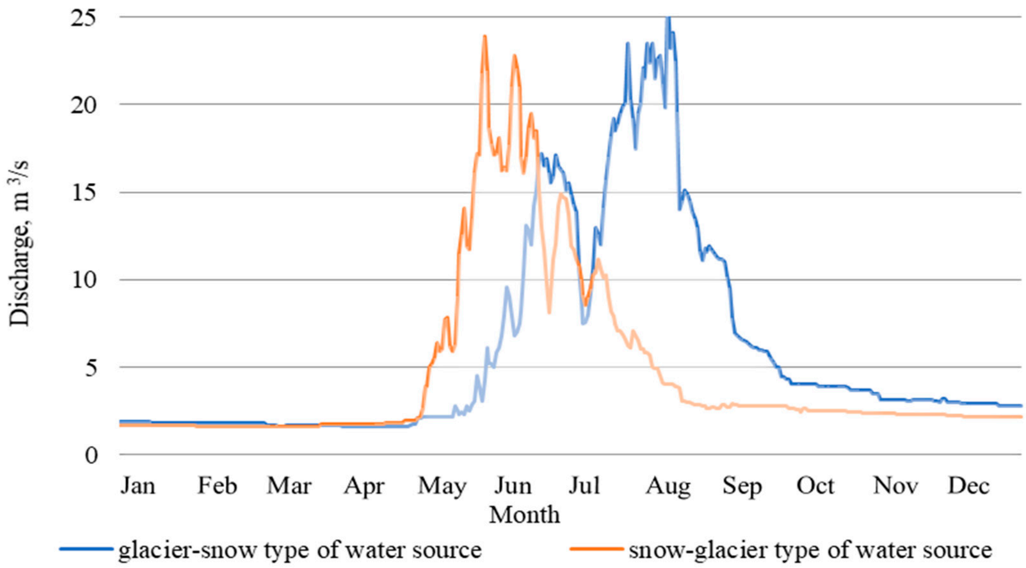

Figure 5. Hydrographs of the mean daily discharge of glacier–snow- and snow–glacier-fed rivers, 2017.

Melted snow water directly depends on the amount of atmospheric precipitation in the cold period (autumn-winter), and melted ice water depends on the sum of positive summer temperatures. However, fluctuations in air temperature and precipitation are often asynchronous, resulting in a lack of synchronism in long-term changes of discharges and meteorological factors such as precipitation and temperature, forming the runoff. Therefore, the water availability of rivers in a particular year depends on the value and ratio of these factors.

In the intra-annual distribution of water discharge, the highest values occurred in the summer months June to September. This is evidenced by the data of the river gauging stations Issyk-Ata, Alamedin, Ala-Archa (Table 8).

Table 8. Interannual variability of flow in glacial –snow-fed rivers as per season (%).

Gauge	Winter (December-February)	Spring (March-May)	Summer (June-September)	Autumn (October-November)
Issyk-Ata–Yuryevka	12.9	12.5	49.6	25.0
Alamedin–Chunkurchak	8.0	20.2	61.3	10.5
Alaarcha–Kashkasuu	7.0	22.0	58.0	13.0

4.2.1. The Current Trend in the Dynamics of Glaciation

The river Shu basin is surrounded by high mountain ranges and has well-developed glaciation. Glaciers are a source of river runoff generation, especially in this region arid climate; they maintain high water availability, even in the driest years when the annual precipitation is lower than the mean annual value [34].

The retreat of a glacier itself is not yet an indicator of a steady reduction in glaciation. Judgement on a glacier state can only be achieved based on long-term data on its mass balance or analysis of large-scale maps of various seasons and years. Long-term mass balance observations were carried out in the Kyrgyz ridge glaciers [14].

Decreased glaciation in the Tien Shan has been observed since the second half of the 20th century. However, this process was the most intensified post-1972. The retreat of glaciation was most pronounced on the slopes of the southern exposure and the ridges with elevations of up to 4200–4500 m [21].

Researchers' opinion in this field is unambiguous in that, against centuries-old fluctuations, glaciers at this stage (especially in the last 40–50 years) are in degradation [49]. This is evidenced by a reduction in their storage and surface areas. The dynamics of glaciation in the river Shu basin can be assessed based on the data for the basin of the river Ala-Archa (Kyrgyz ridge) and the basin of the river Chon-Kemin (Kungei Ala-Too and Zailiysky ridges) [22,37].

The changes of the area of the glaciers in the river Ala-Archa basin are given below:

- 42.83, 40.62 and 36.31 km^2 in 1963, 1981 and 2003, respectively.
- The area of the glaciers decreased by 5.16% (with a 0.29% average annual decrease) and 10.6% (with a 0.48% average annual decrease) in 1963-1981 and 1981-2003, respectively.

The changes of the area of the glaciers in the upper reaches of the river Chon-Kemin basin are shown below [36]:

- The area of glaciers decreased by 9.3% (with a 0.46% average annual reduction rate) in 1955–1979.
- The area of the glaciers decreased by 7.8% (with a 0.32% average annual reduction rate) in 1979–1999.
- The glaciers area decreased by 16.4% (with a 0.37% average annual decrease) for the entire period of 1955–1999.

The future retreat in glacier areas and glacial mass will decrease glacial runoff and reduce the water availability of rivers and glacial–snow river feeding.

4.2.2. Behavioural Reaction of Glacier- and Snow-Fed Rivers to Climate Change

In the average water (or hydrological) year, the share of glacial waters in the annual runoff amounts to 31%, increasing in summer to 52% [34]. In years when the average summer temperature is higher than normal by 0.7–1.4 °C and the amount of precipitation is lower than normal by 27–44%, the contribution of glacial waters increases in annual volume to 40–61%, and in the summer, it rises to 60–90%. Glacial waters fully compensate for the lack of precipitation in such years due to the glaciers intense melting. Therefore, a significant reduction in glaciation will decrease the glacial share of discharge and, consequently, the annual river discharge. First, this will happen in rivers with little glaciation and then in rivers with a significant glacial share in water discharge. This situation is already noted in the Kara-Balta, Kyzyl-Suu (Bakabulak village), and other rivers [14].

4.2.3. Analysis of the River Runoff Dynamics under Conditions of Regional Climate Warming

The patterns of the residual mass curve of mean annual flow in all three cases are typical for rivers with a stable trend towards an increase in discharge (Figure 6). This is especially clearly seen on the rivers Ala-Archa and Chon-Kemin. In the first half of the series, the mean annual flow decreases compared with the average long-term value for the entire period, while in the second half of the series it shows an upward trend. Therefore, in the 70s early 80s, the curve begins to rise. For rivers with high-mountain catchments, where the share of glacial water supply is high, this indicates the shrinking of mountain glaciation on the increase in the flow of rivers.

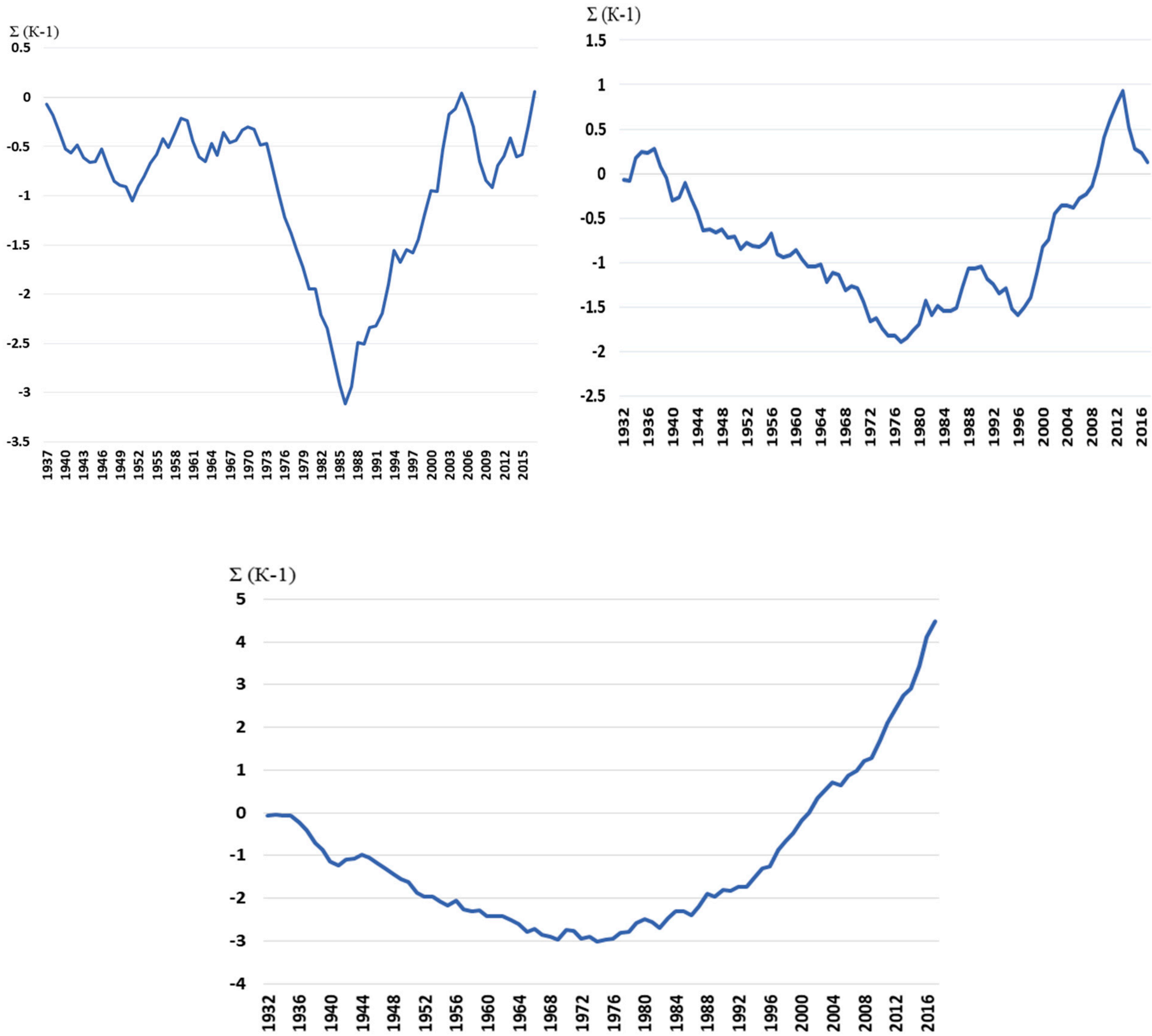

Figure 6. The residual mass curve of mean annual flow for the streams of Shu at Kochkorka (**left**), Chon-Kemin (**right**) and Ala-Archa (**below**).

The share of rainfall increases in the river Shu at Kochkorka; therefore, before 1973, fluctuations in runoff did not have a pronounced tendency; but in the arid period of 1973–1975. Then, the residual mass curve began to fall sharply, and its increase started in the 80s. Therefore, low water levels in 1973–1975 were typical for most of the rivers of this region.

Another essential feature of the degradation of mountain glaciation and a decrease in the share of glacial runoff is an increase in fluctuations in the annual runoff from year to year, even at such a high–mountain gauging station as the river Ala-Archa.

Trend analysis of the average annual water discharge was conducted for the three most characteristic rivers of the Shu basin: the river Shu at Kochkorka (Figures 7 and 8), rivers Chon-Kemin (Figures 9 and 10) and Ala-Archa (Figures 11 and 12). The details of regression analysis are summarised in Table 9. According to the p-value, all the tests are statistically significant ($p < 0.005$). Though this value is very close to the limit for the gauging station Shu at Kochkorka.

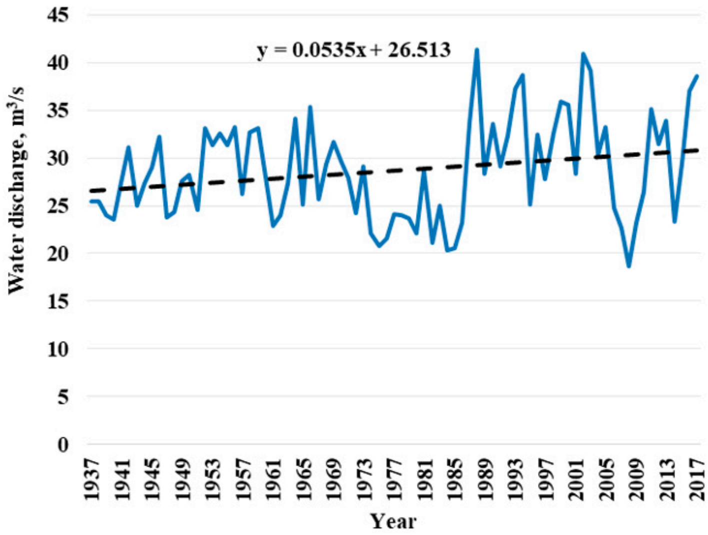

Figure 7. The trend of the average annual water discharge of the river Shu at Kochkorka.

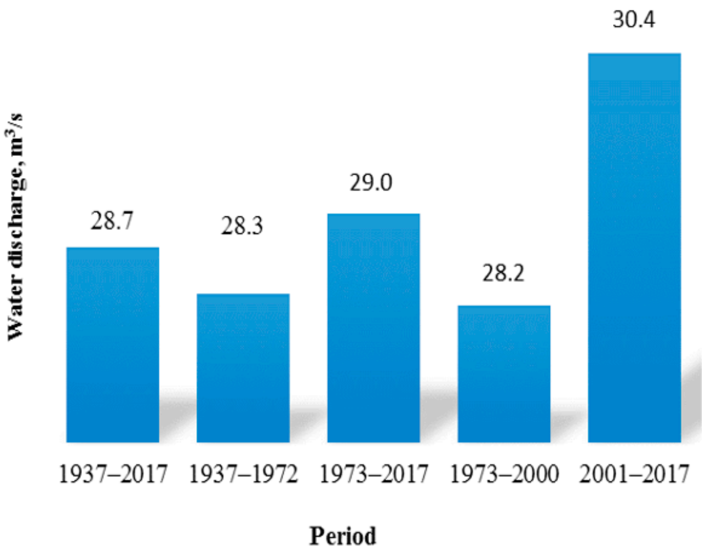

Figure 8. Annual average water discharge of the river Shu at Kochkorka for comparable periods.

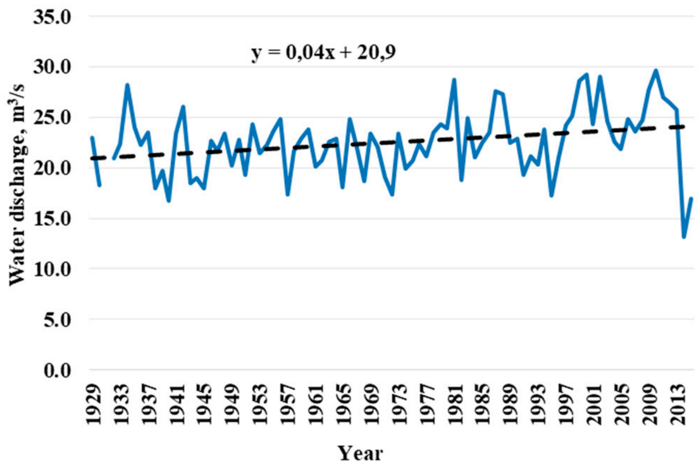

Figure 9. The trend of average annual water discharge of the river Chon-Kemin.

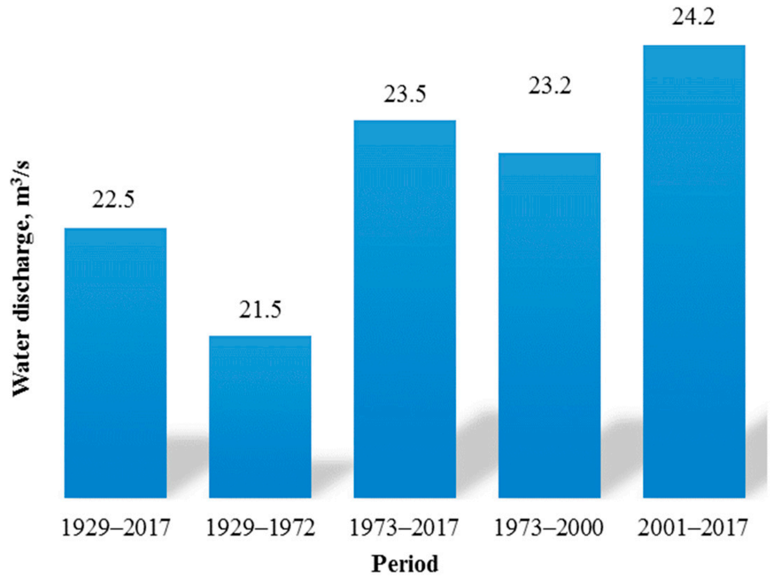

Figure 10. Annual average water discharge of the river Chon-Kemin for comparable periods.

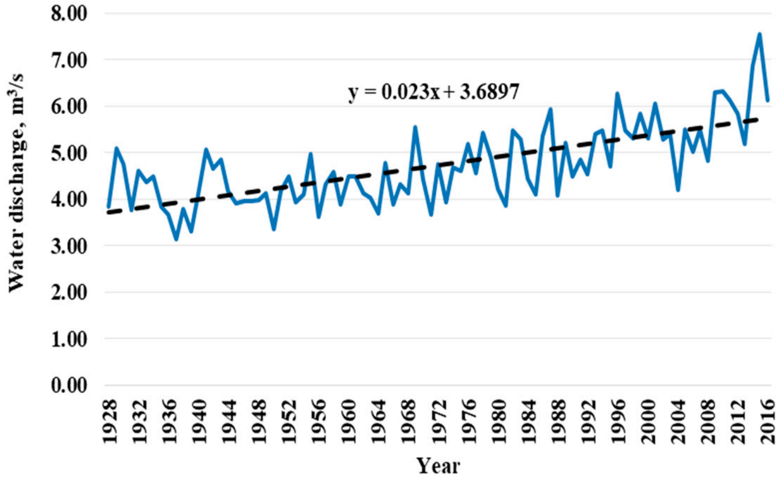

Figure 11. The trend of the average annual water discharge of the river Ala-Archa.

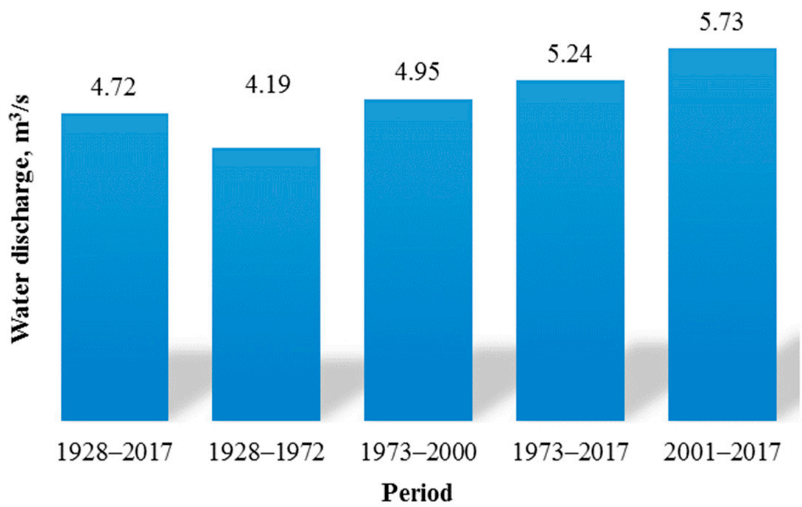

Figure 12. Annual average water discharge of the river Ala-Archa for comparable periods.

Table 9. Summary of regression analysis.

Gauging Station	R Squared	Observations	Standard Error	Intercept	X Variable	F	Significance F	*t* Stat	*p*-Value
Shu at Kochkorka	0.056	81	5.18	26.51	0.053	4.73	0.033	2.17	0.032
Chon-Kemin	0.085	87	3.11	20.85	0.037	7.9	0.0061	2.81	0.006
Ala-Archa	0.49	90	0.6	3.68	0.023	86.2	ca 0	9.28	ca 0

The trends for all of the rivers are uniquely positive. For example, in the river Shu, the average annual water discharge increase for the entire observation period (81 years) from the initial to the final trend values amounted to 3.4 m^3/s (from 27.1 to 30.5 m^3/s), with an average long-term value of 28 m^3/s. In the river Chon-Kemin, the increase of water discharge (record of 88 years) amounted to 3.0 m^3/s (from 21.1 to 24.1 m^3/s), with a long-term average value 22.5 m^3/s. In contrast, the river Ala-Archa (record of 90 years) the same value amounted to 2.0 m^3/s (from 3.82 to 5.82 m^3/s), with an average annual value 4.72 m^3/s.

A alternative and more detailed approach for examining inter-annual variability in climate and flow was proposed [7]. Wavelet spectral analysis for unevenly sampled time series allows characterising pseudo-periodic and non-periodic oscillations just as well as fully periodic oscillations. Using spectral analysis for the time series in the frequency domain, one can better understand the processes which generate their variability and possibly uncover underlying connections between them. Significant shared features in the wavelet spectra of the studied paleoclimatic time series were discovered. The results provided by [6] also highlight the potential of the Least-Squares Wavelet software in analysing climate and hydrological time series without any need for interpolation, gap-filling, and de-spiking. A combination of nonparametric techniques for evaluating trends in streamflow time-series, e.g., the Mann–Kendall test and its modified test, also provides better possibilities [5]. In summary, the spectral components (e.g., inner-annual, annual, semi-annual) of the flow time series shown in Figures 7, 9 and 11 can be detected to see how their amplitude changes over time.

4.2.4. Forecast of the Mean Annual Flow for the Period up until 2050

The comparative analysis results in terms of the average annual discharge for the different estimated periods and the discharge rate of increase are shown in Table 10.

The data given in the figures and table demonstrate that after the 1970s, along with climate change (warming), the increase of water availability in the rivers began. The most significant increase rates in water discharge in the Shu, Chon-Kemin, and Ala–Archa rivers — 0.129, 0.059, and 0.046 m^3/s, respectively, were noted from 2001 to 2017. The most significant increase in temperature was also observed during the same period.

When extrapolating up to 2050, the increased river discharge rates were referred to the period of 2001–2017. With this growing trend for 33 years (by 2050), the mean annual flow should increase as follows: in the river Shu by 4.26 m^3/s and amount to 34.7 m^3/s; the river Chon-Kemin —by 1.95 and amount to 26.2 m^3/s; the river Ala-Archa by 1.52 and amount to 7.25 m^3/s.

Based on the forecast of the glacier reduction by 2050 [37], river flow will also decrease to a minimum, i.e., equivalent to the glacial component. According to [50], in an average water year, the share of glacial runoff (July-September) accounts for 35%, 44%, and 57% for the Shu, Chon-Kemin, and Ala-Archa rivers, respectively. Therefore, when calculating the reduced share of glacial runoff, it shall be deemed that these amounts will decrease the projected runoff by 2050 (Table 11).

Table 10. Mean annual flow for the compared period and the discharge increase rates.

Flow Parameter	Period of Years	Number of Years	Average Discharge m^3/s	Difference m^3/s	Discharge Increase Rate m^3/s/Annual
The river Shu at Kochkorka					
LTMAF	1937–2017	81	28.7		
MAF	1937–1972	36	28.3	−0.4	
MAF	1973–2000	28	28.2	−0.5	−0.018
MAF	2001–2017	17	30.4	2.2	0.129
MAF *	2018–2050	33	34.7		
The river Chon-Kemin (tributary)					
LTMAF	1929–2017	88	22.5		
MAF	1929–1972	43	21.5	−1.0	
MAF	1973–2000	28	23.2	1.7	0.061
MAF	2001–2017	17	24.2	1.0	0.059
MAF *	2018–2050	33	26.2		
The river Ala-Archa (tributary)					
LTMAF	1928–2017	90	4.72		
MAF	1928–1972	45	4.19	−0.53	
MAF	1973–2000	28	4.95	0.76	0.027
MAF	2001–2017	17	5.73	0.78	0.046
MAF *	2018–2050	33	7.25		

Note: LTMAF denotes Long-Term Mean Annual Flow, and MAF represents Mean Annual Flow. MAF *—anticipated value.

Table 11. Forecast of the mean annual water discharge of the rivers for the period up to 2050.

Parameter	Period of Years	Number of Years	Discharge m^3/s
The river Shu			
Projection	2018–2050	33	34.7
Decrease in runoff	VII-IX	35%	12.1
Corrected projection	2050		22.6
Discharge probability 95%	1937–2017	81	22.6
Discharge probability 99%	1937–2017	81	20.5
The river Chon-Kemin (tributary)			
Projection	2018–2050	33	26.2
Decrease in runoff	VII-IX	44%	11.5
Corrected Projection	2050		14.7
Discharge probability 95%	1929–2017	88	17.6
Discharge probability 99%	1929–2017	88	16.1
The river Ala-Archa (tributary)			
Projection	2018–2050	33	7.25
Decrease in runoff	VII-IX	57%	4.13
Corrected Projection	2050		3.12
Discharge probability 95%	1928–2017	90	3.39
Discharge probability 99%	1928–2017	90	3.10

Note: The discharge probability (frequency) of 95 and 99% corresponds to the recurrence interval of 20 and 100 years, respectively.

According to the forecast for 2050, the average annual discharge in river Shu will be 22.6 m^3/s, while the long-term mean annual flow for the observation period shows 28.7 m^3/s (reduced by 21%). It is noted that for the observation period, the average annual discharge with 95% and 99% of probability (low values) accounts for 22.6 and 20.6 m^3/s, respectively.

In the river Chon-Kemin case, the projected average annual discharge will be reduced by 11.5 and amount to 14.7 m^3/s. Thus it is reduced by 35% compared to the average annual value of 22.5 m^3/s for the observation period. As a result, the discharge for the observation period with 95% and 99% of probability exhibits 17.6 and 16.1 m^3/s, respectively.

As for the river Ala-Archa, a decrease in the flow of up to 4.13, the projected value is 3.12 m^3/s. Therefore, the average annual for the observation period is 4.72 m^3/s (reduced by 34%), and the discharge with 95% and 99% of probability accounts for 3.39 and 3.10 m^3/s, respectively.

The average reduction percentage in the upper part of the river Shu basin flow is projected to be 25—30%.

Considering the projected decrease in the runoff of the main glacier- and snow-fed rivers of 25-30% by the year 2050, the basin water availability will decrease. As a result, the flow will amount to 94–88 m^3/s (2.98–2.78 km^3).

This projection is somewhat optimistic compared to those made by other authors and forecasts made according to global climate scenarios, in which runoff reduction accounts for 45% by 2050 [4,51].

The comparison with the minimum values of water discharge was made not by chance but to show which average values of discharge one can rely on in the future and, consequently, what adaptation measures shall be elaborated. Such situations have already occurred in some of the years of the observation period. As a result, water users have adapted and have taken the necessary measures and arrangements in water allocation [52].

Indeed, the share of glacial runoff is significant in the formation of river flows in the river Shu basin upper reaches; however, the situation shall not be considered tragic. It is noted that with the decrease in the glacier share of runoff, precipitation will play a more significant role in the generation of runoff. Such a pattern is based on the climate warming process, which will affect the increase in evaporation dynamics.

5. Conclusions

Based on the results of this analysis, the following conclusions can be made:

1. The trend analysis of the river Shu basin WS showed a regional increase in air temperature amid global warming. The temperature rise began after 1972, and the most significant rise was recorded from 2001 to 2017. The amount of precipitation has not changed significantly, but a slight increase was recorded in the same period of 2001—2017.
2. The increase in temperature has resulted in more active melting of glaciers and decreased mass and thickness. As a result, the mass balance of the glaciers of the Shu basin post-1970s is negative.
3. An increase in the water availability of glacier- and snow-fed rivers was recorded post-1972 due to the more active melting of glaciers (i.e., the glacial component of runoff increased). An increase of water availability in rivers of this type will continue for the next five years, when the glacial share in the annual river runoff is to be decreased to a volume lower than previously recorded.
4. The average annual discharge projection in terms of three rivers of the Shu basin, namely, Shu, Chon-Kemin, and Ala-Archa, was made based on the methodology of the retrospective analysis of runoff and the rate of water discharge increase for the observation period, as well as the further extension of data for the forecast period (until 2050).
5. Considering that glacial runoff shall be reduced to a minimum by 2050, as projected by the glacier reduction forecast, the projected value was adjusted by reducing the

share of glacier runoff. As a result, the mean annual discharge for the considered rivers will likely decrease by 25-30% on average by 2050.

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