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Kyrgyz transboundary rivers' runoff assessment (Syr-darya and Amu-darya river basins) in climate change scenarios

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ABSTRACT

The research was carried out as part of the preparation "Water Resources" section of the 4th National Communication of the Kyrgyz Republic to the UNFCCC. The article presents extensive information on the current state and changes over a long period of observations of water resources, climate and glaciation in Kyrgyzstan (Syr-Darya and Amu-Darya river basins). The representative rivers were selected as the main objects, which are transboundary between Kyrgyzstan, Uzbekistan, Kazakhstan and Tajikistan. The study aims to assess the inter-annual and intra-annual dynamics of the flow of the rivers for the period from 2020 to 2080, based on the climate projections CMIP5 (RCP4.5 and RCP8.5) and CMIP6 (SSP2-4.5 and SSP5-8.5) (IPCC WG II Report, 2022).

The hydrological modeling method in the HBV light and HBV EHT models and the inertial mean annual flow change method were used to estimate changes in water resources. On the rivers of the northern part of the Fergana Valley, the average annual runoff is expected to increase by 1-19%, in the Amudarya river basin (Kyzyl-Suu river) - by 27-64% of the values for 2006-2019. In the Naryn river, water discharge for this period will remain within the current values for 2006-2019. The method of inertial change in the average annual runoff showed an increase in runoff for 2030 and 2040 for all the studied catchment areas by 6-19% of the current values for 2006-2020. The results of the study are intended for decision-makers on the rational use and long-term planning of water resources under climate change.

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1. Introduction

According to the latest assessment of surface water resources of the Kyrgyz Republic, most of them, about 60 %, belong to the Syr-Darya basin, which is of great transboundary importance (Table I) (Mamatkanov et al., 2006). Its main waterway is the Naryn river basin, the flow of which replenishes the Toktogul reservoir (with total capacity of 19.5 km^3) and is used for hydropower purposes in Central Asia, as well as for irrigation of agricultural fields in arid areas of Uzbekistan and Kazakhstan. The basin of the Amu-Darya river has a small area (about 20%) on the territory of Kyrgyzstan, where the source of the Vakhsh river - Kyzyl Suu river is located. The water resources of the Vakhsh river are also of great importance for the Central Asian region, there is the Nurek reservoir (with total capacity of 10.5 km^3), which has hydropower and water management importance for Tajikistan and other countries of Central Asia, located downstream in the Amu-Darya river basin (Uzbekistan and Turkmenistan). The pressure on the river basins is constantly growing: new irrigated lands are being introduced, the construction of reservoirs and cascades of hydroelectric power plants in the Vakhsh river basin is being resumed, the construction of small hydropower plants on the Naryn river is being considered in the future, and the Chatkal River has significant undeveloped potential hydropower resources. This increase in pressure on river systems is a concern for the downstream countries. In our study, we selected the Syr-Darya and Amu Darya river basins for future water resource scenarios.

Table I. Water resources assessment of the Kyrgyz Republic for 2000

№	River basin, lakes	Long-term mean runoff, km^3/year
1	Naryn	14,6
2	Syr-Darya (below the confluence of the Naryn + Kara Darya rivers)	7,31
3	Total for the Syr-Darya river basin	29,8
4	Kyzyl-Suu (western) Amu Darya river basin	1,98
5	Total for the republic including "karasu" rivers	**48,6** **50,5**

Compiled by Mamatkanov D.M. et al.

Since the 1990s, there has been an increase in the flow of the Kyrgyz rivers associated both with increased water release from glaciers under the global warming, and an increase in the volume of snowmelt water in the annual river flow due to increased precipitation during the cold season (Bobushev, Kalashnikova, 2021).

The objectives of the study are to assess the inter-annual and intra-annual dynamics of the flow of transboundary rivers of Kyrgyzstan (basins of the Syr-Darya and Amu-Darya rivers) for the period from 2020 to 2080 based on hydrological modeling and correlation analysis, considering existing trends in meteorological parameters.

The research novelty of the work lies in the application of hydrological modeling in HBV light and HBV EHT to assess future changes in river flow in climate change scenarios. In addition, a description of the river runoff dynamics was obtained over a long-term observation period - from the time the gauging stations were opened (from 1930-1950 to 2020) and trend estimates of river runoff (forecast) for 2030-2040 were calculated.The structure of the article contains sections describing the current state of glaciation, climate and hydrological changes in parameters occurring over the period from 1930 to 2020. The main sections of the article contain the calculation methodology, the results of the prepared scenarios for changes in climate parameters and inter-annual and intra-annual dynamics of river flow for 2020-2080. The discussion includes research material on water resource assessment over a historical period and for the future. The resulting part of the article contains conclusions and recommendations based on the calculation results.

The main sources of feeding of Kyrgyz rivers are snow cover and glaciers, with snowmelt runoff having the leading role (Shults, 1965; Shcheglova, 1960). Studies have shown that in the Tien Shan, snow accounts for up to 70 % of the total precipitation and provides 60% of the total river runoff (Aizen, 1995). Glacial runoff in the rivers of the Syr-Darya basin is less than 13 % of the annual runoff, excluding high-mountain watersheds, for example, in the upper reaches of the Naryn river it occupies 34 %, and on the Kyzyl-Suu river (Amu-Darya) – 23 % of the annual runoff (Konovalov, 1985). The base flow should also be noted (including the entire underground runoff that serves as the base of the hydrograph), which is stable and plays the role of a natural long-term regulator. In most rivers of the Syr-Darya basin, it amounts to 30% or more, and in the rivers of the southern edge of the Fergana valley and in the basin of the Kyzyl-Suu (western) river, it amounts to 60 % or more of the annual flow (Shults, 1965).

Recent studies have shown that mountain communities in developing countries are more economically and climatically vulnerable, than those in the plains and other regions. The degree of climate vulnerability of rural communities in the Pamir and Tien Shan mountains is difficult to understand due to limited data and knowledge of the ecological and socio-ecological context. It was indicated that the vulnerability of mountain communities in Central Asia is due to poor accessibility, rugged terrain, mountain-specific hazards and scarce resources (Xenarios et al., 2018).

The relevance of the research is emphasized by the intensification of conflicts in the basins of the transboundary rivers of Kyrgyzstan, Kazakhstan and Tajikistan, which, under changing climate, leads to competition for water and land resources.

Studies conducted in the most conflict-prone areas of these countries have identified key risks associated with an arid climate, increasing water scarcity, and high agricultural vulnerability. Governmental organizations, relevant state agencies and ministries, commissions on the use of water facilities were given specific recommendations in order to prevent the escalation of transboundary conflicts, as the situation with the identified key risks remains for the future (Impact of climate change on conflict dynamics in the transboundary river basins of Kyrgyzstan, Kazakhstan and Tajikistan: a brief summary of the study, 2021).

2. Materials and methods.

2.1. Objects of study and key river basins

Key river basins were selected for this study, that are representative and indicative of the flow formation zone of the Syr-Darya and Amu-Darya basins in the territory of Kyrgyzstan (see table 3 in chapter results). The feeding of the rivers in the northern and southern edges of the Fergana valley (Syr-Darya basin) differs greatly. For the rivers of the northern edge of the Fergana valley, which are predominantly snow and glacier fed, the basins of the Chatkal and Kara-Darya rivers are indicative. The Kyzyl Suu(western) river, which are glacier-snow fed have a tight flow regulation (the base flow is 60-70% of the annual), due to the peculiarities of the geological structure in the river basin. Finally, the basin of the Naryn river is singled out separately, with calculations made in the alignment of the Naryn town. The location of the basins in Kyrgyzstan and Central Asia is shown in Figure 1. Main characteristics of the basins up to the observation points are given in Table II.

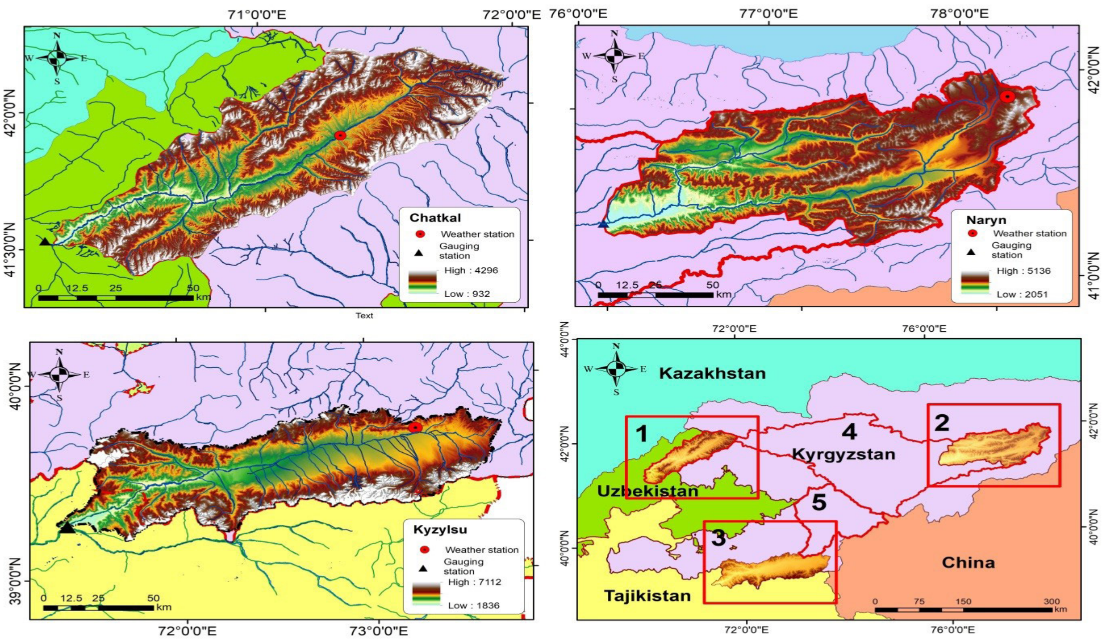


Fig.1. Location of the studied river basins on the territory of Kyrgyzstan and the countries of Central Asia. 1 – Chatkal river basin, 2 – headwaters of the Naryn river, 3 – Kyzyl-Suu river basin, 4 – tributary to Toktogul reservoir, 5 – Kara-Darya river basin – tributary to the Andijan reservoir.

Table II. Basic information about the river basins under study*

№	Name of the gauging station	Catchment area in km^2	Mean catchment elevation in m.a.s.l.	Glacier area			Mean annual water discharge in m^3/s
				1940-1970s, in km^2	*2013-2016, in km^2	percentage of the basin area*	
1.	r. Naryn- Naryn town	10500	3570	618,6	511,4	4,9	92,9
2.	the Naryn river - tributary to the Toktogul reservoir.	52187	2851	-	1063	2,0	404
3.	r.Chatkal-Khudoydodsay	6602	2652	51,2	42,3	0,6	110
4.	the Kara-Darya river- tributary to the Andijan reservoir.	12561	2585	106,7	105	0,8	123
5.	r. Kyzyl-Suu - Dombrachi	8470	3540	640,3	578,4	6,8	76,2

Note: *- glacier area according to Landsat images for 2013-2016. Compiled by the author.

Mean elevation of the studied catchment area is 2600-3500 m above sea level, the glaciation area is different - 0.6 - 6.8 % of the basin area. The Kyzyl-Suu River (western) and the upper Naryn river (Naryn town) are glacier-snow fed rivers (catchment area elevation is 3540-3570 m.a.s.l.), and the Chatkal, Kara-Darya and Naryn rivers are snow-glacier fed rivers (catchment area elevation is 2585-2851 m.a.s.l.).

2.2. Changes in climatic factors over a long-term observation period

The climate of Kyrgyzstan is characterized by continentality, aridity, altitudinal zonality and large spatial differences (Atlas of the Kyrgyz SSR, 1987).

Climatic changes in the Tien Shan mountains affect the inter-annual and intra-annual distribution of river flow. Global warming, which began in the last century and has intensified since the 1970s, is accompanied by an increase in the annual precipitation in the Tien Shan mountains. There is an increase in the duration of the warm period, over the past 20 years, according to weather stations in the Naryn river basin, the transition of positive air temperatures through 0 oC is observed 10-15 days earlier, and towards negative temperatures later. And an increase in precipitation during the cold period, leads to an increase in the role of snowmelt and a decrease in glacial runoff in feeding the rivers of the Tien Shan (Kalashnikova, 2017).

Analysis of changes in air temperature and precipitation for the major river basins over the 70-85 year period shows positive trends, except for the Tien Shan, Suusamyr and Jalal-Abad weather stations.

For the rivers of southwestern Kyrgyzstan according to 7 weather stations (Chatkal, Sary-Tash, Ak-Terek-Gava, Uzgen, Batken, Pacha-Ata, Jalal-Abad) the warming rate for annual temperatures obtained by linear trend for 1930-2015 was 0.174 °C/10 years (1.3 °C per period). The warming across the territory was accompanied by an increase in annual precipitation at a rate of 9.3639 mm / 10 years or by 76 mm (by 12 % of the average value for the observation period for the period 1930-2017), while during the period of 1976- 2017 it amounted to 20% of the period 1930-2017 (Podrezova, Pavlova, 2019).

In the Tien Shan high mountains the warming has significant features during the period of 1930-2015, which is connected with the location of the basin within the mountain system of the Tien Shan, closed from the moist carrying air masses, having a highland and sharply continental climate. Thus, according to the Tien Shan weather station (altitude 3635 m), there is a steady increase in the mean annual air temperature by 0.188 ° C/10 years, while it was 3 times higher from 1976 to 2015. At the time of an increase in air temperature, the amount of precipitation in general decreased at a rate of -7.88 mm/10 years, which amounted to 22% of the 1961-1990 norm (Podrezova, Pavlova, 2017). According to Naryn weather station, there is a slight increase in the amount of precipitation during the cold period (October-April) by 2.082 mm/10 years, during the warm period (May-September) by 1.462 mm/10 years (Kalashnikova et al., 2020).2.3. Changes in the area of glaciation and in the number of glaciers.

Global warming leads primarily to the melting of glaciers in the mountains and to the degradation of glaciation. According to Landsat images for 2013-2016, the area of glaciers in the Tien Shan river basins has decreased by 10-47 % compared with the data of the USSR glaciers catalog (1940-1970). Over a period of about 70 years, the area of glaciation in Kyrgyzstan has decreased by 16 %, the area of large glaciers has decreased by 17 %, while the area of small glaciers has increased by two and a half times. This is due to the general degradation of glaciation, in which the degradation of large glaciers leads not only to a decrease in their area, but also to their disintegration into separate parts, which function as independent small glaciers. The total number of glaciers increased by 22 %, which is due to an increase in the number of small glaciers (less than 0.1 km^2 in size) by two and a half times (by 258 %), while the number of large glaciers (more than 0.1 km^2 in size) decreased by 7.5 % (Shabunin, 2018)

Almost half of the glaciation of the country is in the Tarim river basin (45 %) and the third part is in the Syr-Darya river basin (30%). Reduction of glaciation area in the Syr-Darya river basin is 15 % (in Naryn and Chatkal river basins - 17 %, in Kara-Darya river basin - almost unchanged), in Amu Darya river basin - 10 % (Table 1).

Large glaciers of complex valley and trough morphological type in the basins of the Syr-Darya and Amu-Darya rivers are located in the upper reaches of the Naryn river (a tributary of the Chong Naryn) and in the basin of the Kyzyl-Suu river (western).

Field studies for the period from 2011 to 2020, available on the “World glacier monitoring service” website (https://wgms.ch), show a negative mass balance of glaciers in the Syr-Darya and Amu-Darya basins. The exceptions are some years on the Abramov glacier (the southern edge of the Fergana Valley) and 2020, where a positive mass balance was noted (the exception is glacier No. 354 in the upper reaches of the Naryn river).

2.3. Climate projections for calculation river runoff for the future and corrected offsets.

An analysis of climate projections was carried out using global atmospheric and oceanic general circulation climate models (AGCMs) Coupled Model Intercomparison Project Phase 5 (CMIP5) and Coupled Model Intercomparison Project Phase 6 (CMIP 6), available on the Earth System Grid Federation platform portal (https://esgf. llnl. gov /), and combined into an ensemble.

An ensemble approach is applied using the results of different models shows the highest success in reproducing average climatic characteristics when compared with observational data. This is due to the fact that the systematic errors inherent in each model individually are often random in relation to the ensemble of models and, when compiling the ensemble, are mutually compensated Application of ensemble models gives possibility to obtain more reliable distributions of basic characteristics of regional climate.

In the literature, it is not recommended to use only one model, but to use a multi-model approach - the use of forecasts from several models (ensemble), since the ensemble mean reduces the errors of a single model. (Flato et al., 2013; Gleckler et al., 2008; Knutti et al., 2010).

CMIP5 future climate projections were used in this article, which are represented by the average data of the ensemble of 21 models for global fields of daily averaging data for two representative scenarios greenhouse gas concentration: RCP4.5 and RCP8.5 (RCP4.5 and RCP8.5 in the English version). The scenario index characterizes the magnitude of anthropogenic radiation forcing achieved in 2100, namely: RCP4.5 is the stabilization scenario, according to which the radiation forcing will stabilize at about 4.5 W/m2 by 2100; RCP8.5 is the high radiation scenario, under which it will continue to grow after 2100. Under this scenario, concentrations would not stabilize until 2250, in this case, the concentration of CO_2 will be about 2000 ppm, which is about 7 times higher than its pre-industrial level.

Also CMIP6 scenarios were used, where temperature anomalies were considered and ensemble averages of 25 models were prepared for two SSPs (Shared Socioeconomic Pathways) scenarios: SSP2-4.5 and SSP5-8.5. Scenario SSP2-4.5- an update of RCP4.5 based on SSP2, is associated with a stabilization of the population by the end of the century, and with a decrease in intensive use of resources and energy. SSP5-8.5 - an update of RCP8.5 based on SSP5, characterized by rapid technological progress, exploitation of fossil fuel resources, and at the same time by significant investments in health care, education, and environmental issues (Riahi et al., 2017).

The list of used global climate models is presented in Annex 1.

The regionalization of the calculated data of each of the global climate model was carried out by the maximum and minimum daily air temperature, as well as by the daily amount of precipitation into the nodes of the coordinate grid 0,25° x 0,25 ° (or 25 x 25 km), which improves the spatial detailing of climatic data and their use in the tasks of assessing the impact of climate change.

A statistical method was used to fit the latitude-longitude grid, the results of which are presented on the NASA NEX platform (National Aeronautics and Space Administration, NASA Earth Exchange, https://cds.nccs.nasa.gov).

All results of calculations for each model on the NASA NEX platform already contain a correction for a systematic error in the models, the correction was made in accordance with the BCSD method (Thrasher et al, 2012). The algorithm compares the results of the AGCMs with the corresponding climate observations for a common period and uses the information obtained from the comparison to adjust the climate forecasts to better match the historical climate data for the region under study.

Climate models are the most appropriate tool for estimating future global and regional climate change (Yang et al., 2010; Flato et al., 2013; Otero et al., 2018). However, due to imperfect conceptualization, spatial averaging or discretization, biases and systematic errors occur in climate models (Fowler et al., 2007; Teutschbein and Seibert, 2012).

In this work, a simple and widely used scaling method was applied for further hydrological modeling. The scaling method is performed by adding the difference between the observations and historical temperature modelling and adjusting the forecasted temperature modelling. In the case of precipitation, the forecasted precipitation is corrected by multiplying by the ratio of observations to historical modelling (Teutschbein and Seibert, 2012; Chen et al., 2013; Xu, 2018).

2.4. Methodology for estimating river flows for the future

The article discusses the mountain rivers of Central Asia (the territory of Kyrgyzstan) with different types of feeding (snow-glacial and glacier-snow), subdivided in accordance with the classification of Schulz. The classification is based on formal criteria: the ratio of the runoff for the period July-September to the runoff for March-June and its percentage contribution to the annual runoff and the month with the maximum runoff (Shults, 1965, Shcheglova, 1960).

As a method for studying the cyclicity in the course of mean annual water discharges, the authors used the difference total runoff curve (synonym: reduced total runoff curve), which can be represented by the following formula (Chebotarev, 1964):

$$W_{diff} = \sum (Q - Q_0)\Delta t \tag{1}$$

where W_{diff} is the ordinate of the difference total curve, which depicts the increase not in the total runoff of the river, but in the difference between the actual discharge Q and the constant discharge Q_0, taken equal to or close to the average value for the period. When studying the patterns of long-term runoff fluctuations, the reduced total runoff curve is constructed by summing the deviations of the modulus coefficients from the middle. In this case, the ordinates of the curve, equal to $\sum_i^1 (K-1)$, give at the end of each i-th year an increasing sum of deviations of the annual modular coefficients K from the long-term average value or norm (¯K= 1). Synonymous with integrated runoff curve. This method is widely used to study the cyclicity in long-term fluctuations in runoff to restore natural runoff under conditions of climate change or under conditions of anthropogenic interference (domestic runoff study) (Bobushev, Kalashnikova, 2021, Shivareva, Galaeva, 2014, Lineytseva, 2009).

Hydrological models HBV light 2.0 and HBV3-ETH9 were used for river runoff calibration and calculation for the key basins of Kyrgyzstan for future periods. The HBV model was developed in 1973 at the Swedish SMHI (Swedish Meteorological and Hydrological Institute) and further it was improved at the ETH Zurich (Bergstörm, 1992; Braun, Renner, 1992; Hottelet et al., 1993). The model has been modified many times, and there are various versions in many countries. Currently, the model has a user-friendly interface that allows to visualize data and retrieve them both in graphical form and in the form of tables. The "runoff – precipitation" model HBV3-ETH9 we use to calculate runoff of high mountain rivers is an advanced model HBV, which allows to calculate the daily runoff hydrograph based on meteorological and hydrological ground observation data. The HBV3-ETH9 model has a simple non-deterministic structure and does not require a large set of meteorological parameters. Another model that we use is HBV light 2.0 with semi-distributed parameters, which includes subroutines for meteorological interpolation, calculation of snow accumulation and snowmelt, total evaporation, soil moisture, and runoff generalization to calculate the transformation of water movement across rivers and lakes. There was a division into altitudinal zones for all watersheds above 200 meters.

The choice of these models was due to the fact, that they are freely available and do not require a license. The HBV light 2.0 model has a simple interface and a small set of input data: daily data on air temperature, precipitation and evaporation from a weather station representative of the watershed, average daily water discharge from a gauging station with natural flow. Hydroposts should be located at the exit from the mountain gorge, as well as located above the points of water intake for irrigation and communal needs. Preparation of data in GIS required a digital elevation model with a spatial resolution of 30 meters (https://earthexplorer.usgs.gov) and shp.files of modern glaciation, digitized for 2013-2016 using Landsat8 images (Shabunin, 2018). Data preparation, work with the model, and model optimization were carried out according to the HBV ligh 2.0t user manual (Jan Seibert, 2005). The authors of the article used the allowable ranges of the model parameters given in the manual and in the materials of previous studies for the mountain rivers of Kazakhstan (Bolatova A., 2014). Model HBV3-ETH9 calculates in Matlab and has the same set of input data as well as glacier mass balance data. The modeled data on the mass balance of the Abramov Glacier for 2012-2016 from Martina Barandun work (Barandun , 2018) were used in the calculations. Data preparation, work with the model, and model optimization were also carried out according to the HBV3-ETH9 user guide (Konz M, 2003). Parameter ranges for model optimization were taken from previous studies prepared for the Enylchek of the Central Tyan Shan River (Mayr, 2014).

Future runoff calculations for the Naryn River (Naryn town) were made using the HBV light 2.0 hydrological model, since it does not require the inclusion of glacier mass balance, and for the Chatkal and Kyzyl-Suu rivers, the HBV3-ETH9 model was used with the available Abramov Glacier mass balance data.

To calibrate the model, we used data periods from 2010 to 2019 for the Naryn river and from 2012 to 2016 for the Chatkal and Kyzyl-Suu rivers.The data from gauging stations of Chatkal river - Khudoydodsay, Kyzyl-Suu river - Dombrachi and Naryn river - Naryn town, and weather stations Chatkal, Sary-Tash and Tien-Shan, located mainly in the upper reaches of the studied river basins (Fig.1) were used for future calibration and calculations. The data for the calculations were obtained from the historical data archive of the national hydrometeorological services under existing agreements with scientific institutes.

In addition to hydrological modeling, there was the use of the method of correlation analysis or inertial change in the average annual runoff, if the trend over a long-term observation period was maintained, implemented in Excel tools (Goroshkov, 1979, Podrezov, 2020). The method is widely used to forecast hydrological and meteorological values for the next 10-20 years (Mamatkanov et al, 2006, Podrezova, Podrezov 2021). Unlike water resource change scenarios that can be prepared using hydrological modeling, the method of inertial change in the runoff is recommended to be used for a short period of time - no more than 10-20 years (Mamatkanov et al, 2006, Goroshkov, 1979).

The method of inertial change in the mean annual runoff is represented by a regression equation that expresses the statistical dependence of one variable (Y) on another (X), for the case of a variable correlation (Goroshkov, 1979):

$$Y_1 - \overline{Y} = r\frac{\delta_y}{\delta_x}(X - \overline{X}) \quad (2)$$

where $\overline{Y}$, $\overline{X}$ - are the average values of Y_1 and X_1 ; σ_y and σ_x - are the standard deviation of Y1 and X1 values; r – is the correlation coefficient.

In the regression equation, years are taken as X1 (duration of observations), Y1 is the mean annual runoff of each specific year. According to these values, trends (linear regression relationships) of the mean annual river runoff by years were constructed.

According to the regression equations describing the dependence of variables:

$$y = K_x + z, \quad (3)$$

where K- is the trend coefficient; x- is the number of years for which the mean annual water discharge was calculated (projected) and z- is the free term of the equation representing the initial value of the trend line.

To analyze further calculations, we took K- the trend coefficient, indicating the gradient (value) of the runoff change over the years.

Based on the obtained trend equations, trend estimates of the mean annual water discharges for the selected river basins were calculated.

3. Research results

3.1. Assessment of changes in river flow for the past and future periods

Several main basins can be distinguished on the territory of the Kyrgyz Republic, marked in Fig. 2.

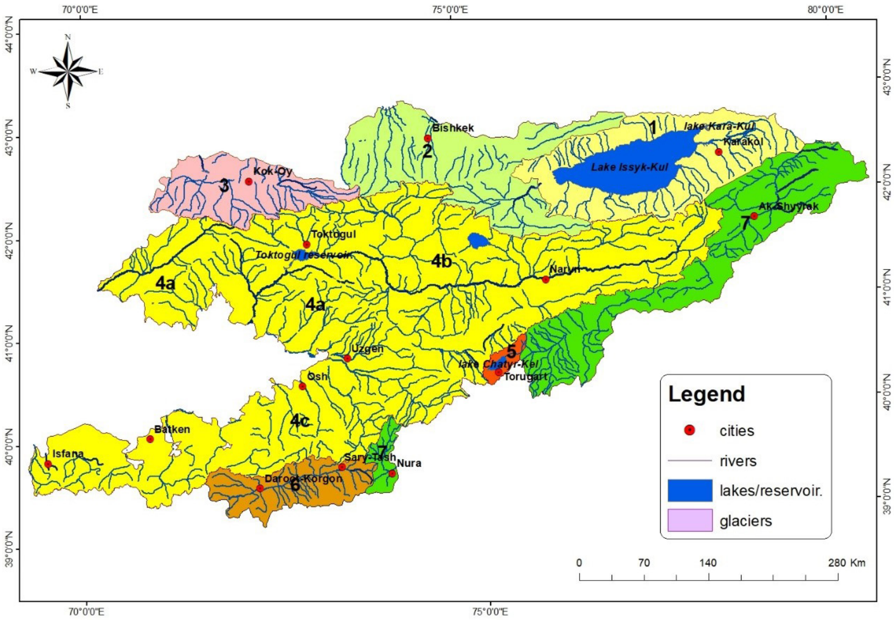


Fig.2. 1 - Issyk-Kul lake, 2 - r. Chu, 3 - r. Talas, 4a - rivers of the northern edge of the Ferghana Valley (Syr-Darya river), 4b – r. Naryn (Syr-Darya river), 4c - rivers of the southern edge of the Ferghana Valley (Syr-Darya river), 5 - Chatyr-Kul lake, 6 - r. Amu-Darya, 7 - r. Tarim.

The key river basins for which the calculations were made were selected based on their indicativeness (or representativeness) for the hydrological regime of the major basins (northern edge of the Fergana Valley, Naryn river basin. For each major basin, its total runoff was calculated for the period from 1945 (1950) to 1991 (1993), when observations were made at the maximum number of gauging stations. Due to the fact that almost half of the network of hydrological stations that existed before 1991 is now closed, for some basins the correlation of water discharge at key rivers was more indicative with the flow of the largest and most water-bearing rivers of the major basins, where observations did not stop and modern data are available.

The correlation coefficient of the average annual flow of the selected representative river with the total average annual flow in the major basins is shown in Table III.

Table III. Correlation coefficient (R) of the average annual flow of the selected representative river with the total average annual flow in the major basins

№	Name of the river – gauging station and its major river basin	R
1.	r. Naryn - Naryn town / Naryn river basin to the HPP cascade on the Toktogul reservoir.	0.79
2.	r. Chatkal - Khudoydodsay / northern edge of the Fergana Valley (Padysha-Ata, Kegart).	0,78
3.	r. Kara-Darya - a tributary to the Andijan Reservoir. / Northern edge of the Fergana Valley.	0,84

Compiled by the author.

A difference integral curve was built to determine the cyclicity in changes of mean annual runoff of rivers with different types of feeding, which traced two synchronous cycles for them: from 1945 to 1992 (2000) - a gradual decrease in the flow and from 1990s (2000s) to 2020 - increase in the flow (Fig. 3).

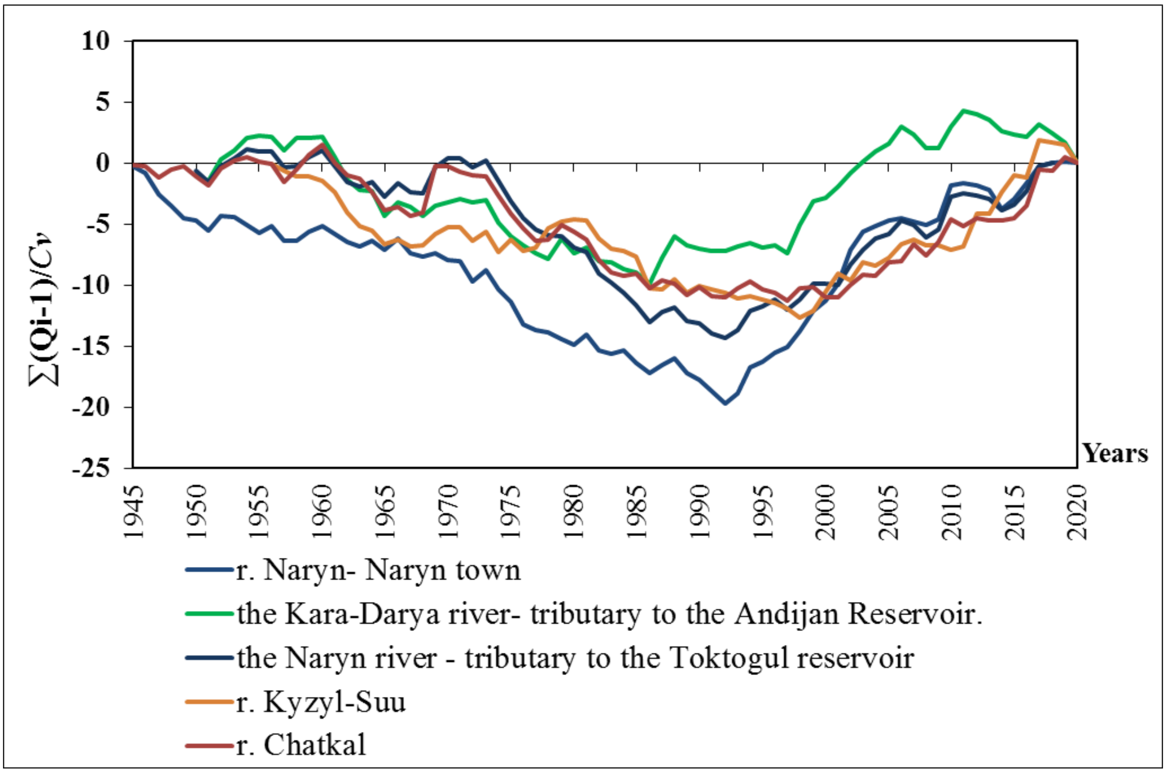


Fig. 3. Difference integral curve of average annual water discharges

The average annual water discharge from 2000 to 2020 increased by 4-16% in comparison with the values for the entire observation period from 1933 (1950, 1955) to 2020 (Table IV).

Table IV. Changes in water discharge for the key rivers of Kyrgyzstan

№	The name of the river - gauging station	Water discharges in m^3 /s and as a percentage of the observation period		
		for the entire observation period, m^3/s	2000-2020, m^3/s	2000-2020 as a percentage of the entire observation period
1	r. Naryn – Naryn town	93,2	106	111
2	the Naryn river - a tributary to the Toktogul reservoir	409	454	110
3	r.Kara-Darya - a tributary to the Andijan Reservoir	123	131	104
4	r.Chatkal-Khudoydodsay	110	127	116
5	r.Kyzyl-Suu - Dombrachi	76,2	80,1	107

Note: * - see Fig. 2 for the observation period. Compiled by the author

The greatest inter-annual variability over the long-term observation period was in the runoff of the Kara-Darya river, which is indicative of the rivers of the northern edge of the Fergana Valley, where the runoff depends to a greater extent on seasonal snow reserves.

The average annual water discharges in all rivers show an increase in river flow (Fig.4). From the 1990s, 2000s to the present, an increase in the number of high-water years can be noted.

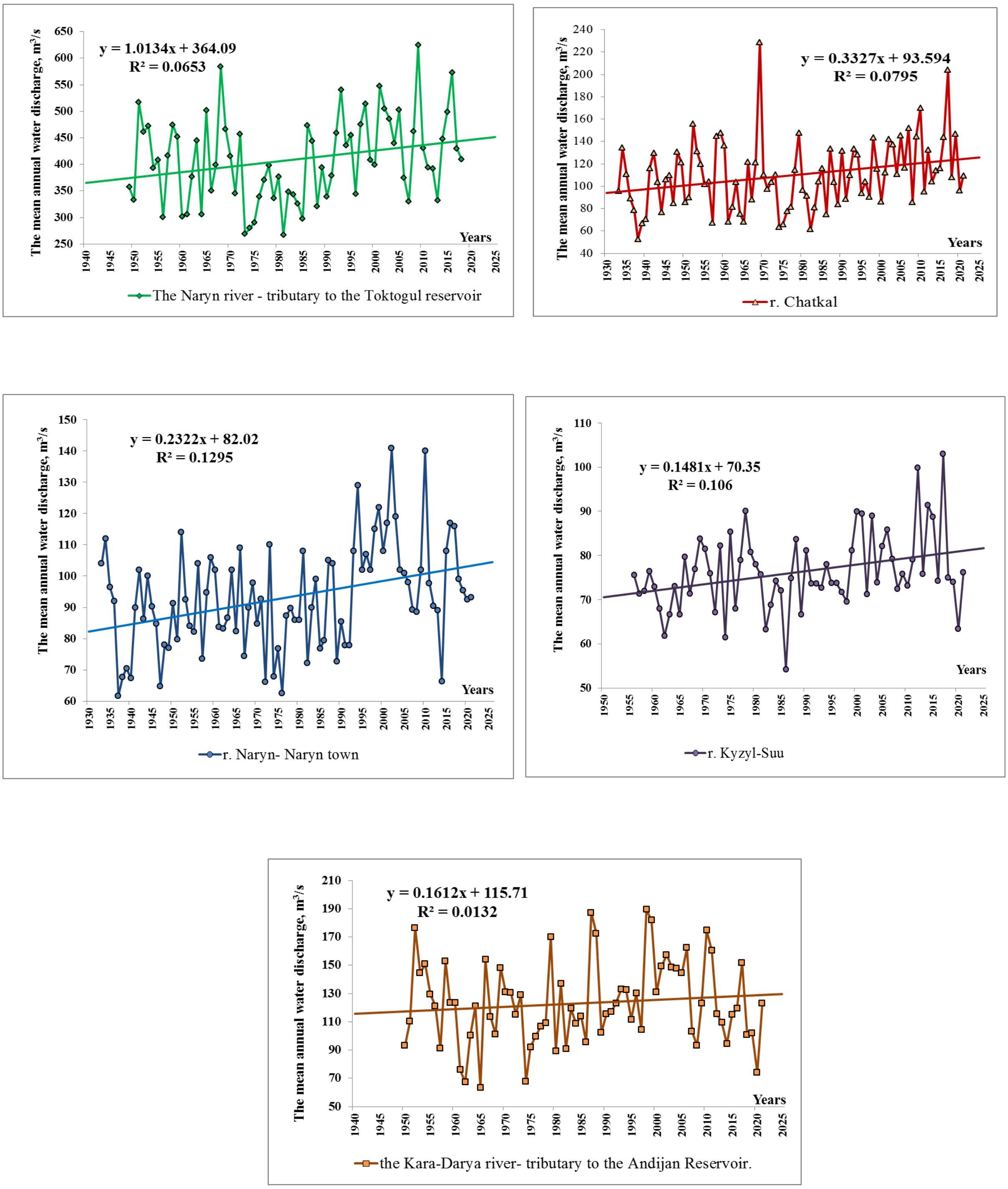


Fig.4. Changes in the mean annual water discharges in the rivers of the Syr-Darya and Amu-Darya basins.

Calculations of future runoff for 2030 and 2040, made using regression equations, show an increase in runoff for all watersheds: in the Kara-Darya river basin by 6-8%; the Kyzyl-Suu river by 9-11%; the Naryn and Chatkal rivers by 13-19% (Table V).

Table V. Water discharge estimates for 2030 and 2040 for the rivers of the Syr-Darya and Amu-Darya basins.

№	The name of the river - gauging station	Average water discharge for the entire observation period, m^3/s	Water discharge over the years			
			2030		2040	
			m^3/s	in % of the norm	m^3/s	in % of the norm
1.	r. Naryn – Naryn town	92,9	106	114	108	116
2.	the Naryn river - a tributary to the Toktogul reservoir.	404	458	113	468	116
3.	r. Chatkal-Khudoydodsay	110	128	116	131	119
4.	r. Kara-Darya - a tributary to the Andijan Reservoir.	123	131	106	132	108
5.	Kyzyl-Suu – Dombrachi	76,2	82,7	109	84,3	111

Compiled by the author.

3.2. Projections of changes in air temperature and precipitation up to 2100

Scenarios for changes in air temperature and precipitation are shown in Figures 5 and 6. The Tien-Shan, Sary-Tash, and Chatkal weather stations located in the runoff formation zone of the selected key rivers are representative for runoff calculations. All calculations derived from the available model ensembles for CMIP5 and CMIP6 have been checked for consistency with the available trends in the historical series of observations. As a result, for runoff calculations the CMIP5 RCP4.5 and RCP8.5 scenarios were chosen for the Tien Shan and Sary-Tash weather stations, and the CMIP6 SSP2-4.5 and SSP5-8.5 scenarios were chosen for the Chatkal weather station. According to the obtained scenarios of air temperature changes, a gradual increase in air temperature up to 2100 can be noted. The deviation of mean annual air temperature values by 2100 in the CMIP5 RCP4.5 and CMIP6 SSP2-4.5 scenarios will be up to 2.2 oC, in the CMIP6 SSP5-8.5 scenario up to 3.7 oC, the largest deviation - in the CMIP5 RCP8.5 scenario up to 5.7 °C.

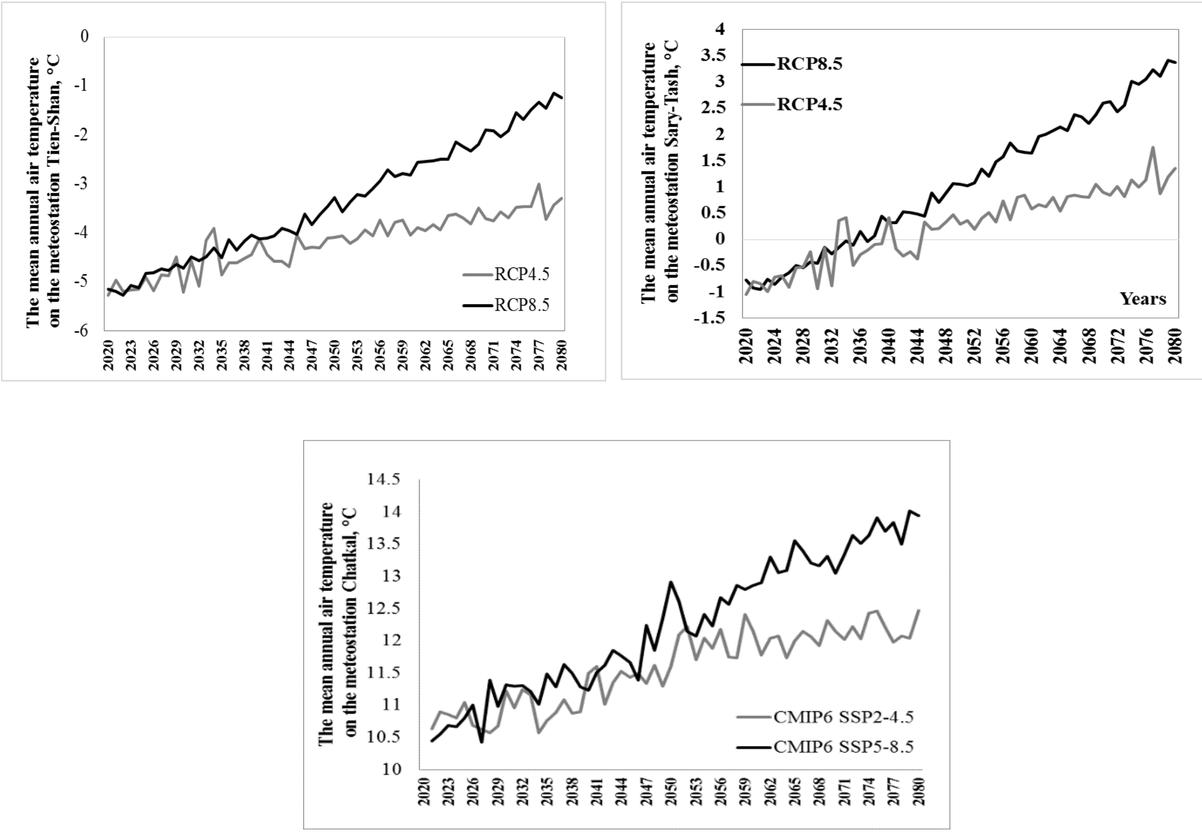


Fig. 5. Air temperature change scenarios according to meteorological stations representative for river runoff calculations.

Mean annual precipitation fluctuates in the following ranges at weather stations: Tien Shan - 70-85%, Sary-Tash - 80-120% and Chatkal - 90-120% of the values for 2006-2019. Inter-annual variability of precipitation is significant and has a sawtooth curve, the variability of precipitation increases from 2040-2050 to 2100.

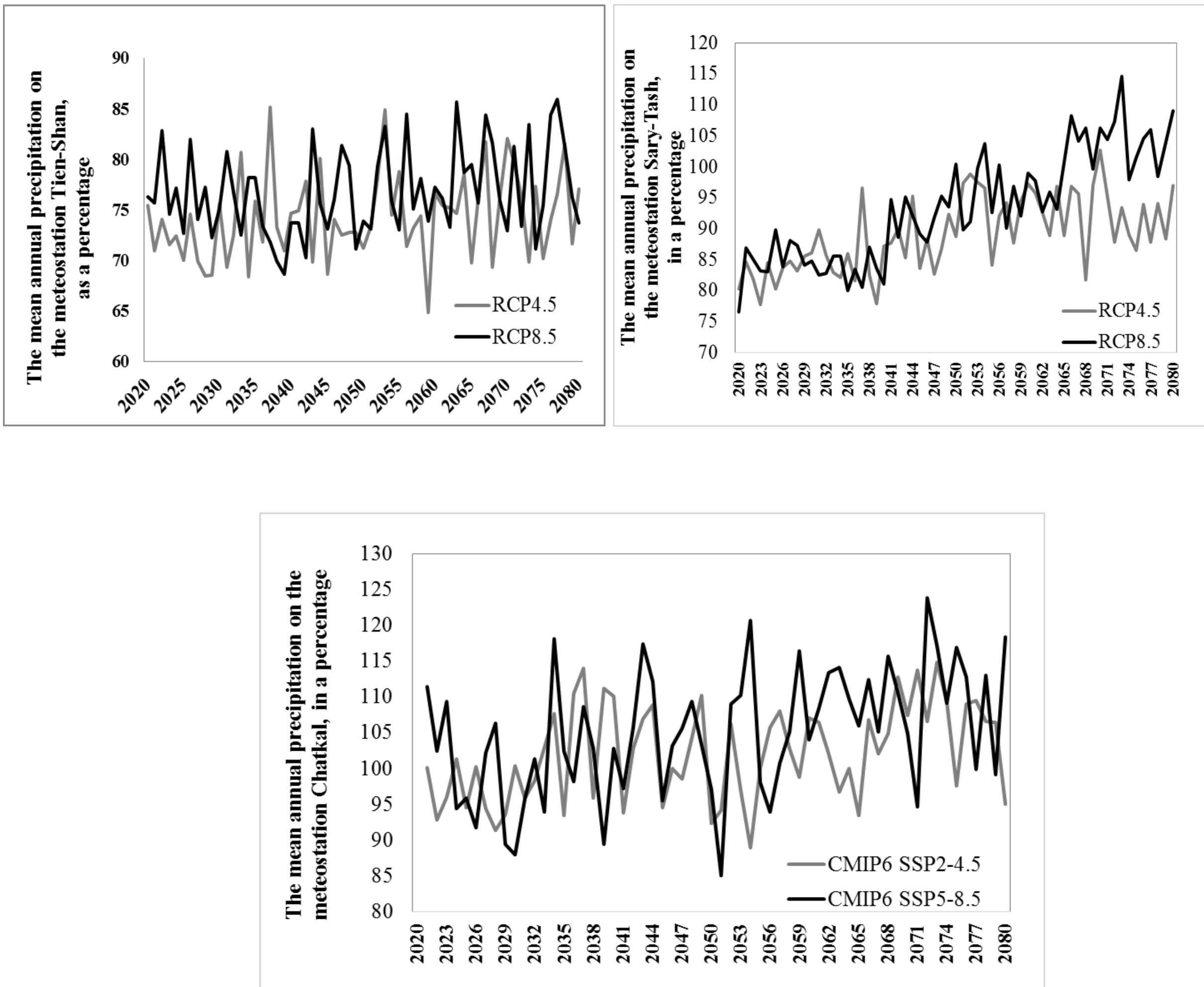


Fig. 6. Precipitation change scenarios based on weather stations representative for river runoff calculations.

Precipitation change scenarios in the Kara-Darya river basin did not give results consistent with trends over a long-term observation period. Therefore, calculations for this basin by the method of hydrological modeling were not possible.

3.3. Runoff change in key river basins up to 2080

For the selected basins, the HBV-light HBV-EHT models were calibrated, which showed the following results: for river basins (Fig. 7): Naryn R2 = 0.83, Chatkal R2 = 0.95, Kyzyl-Suu R2 = 0.82 .

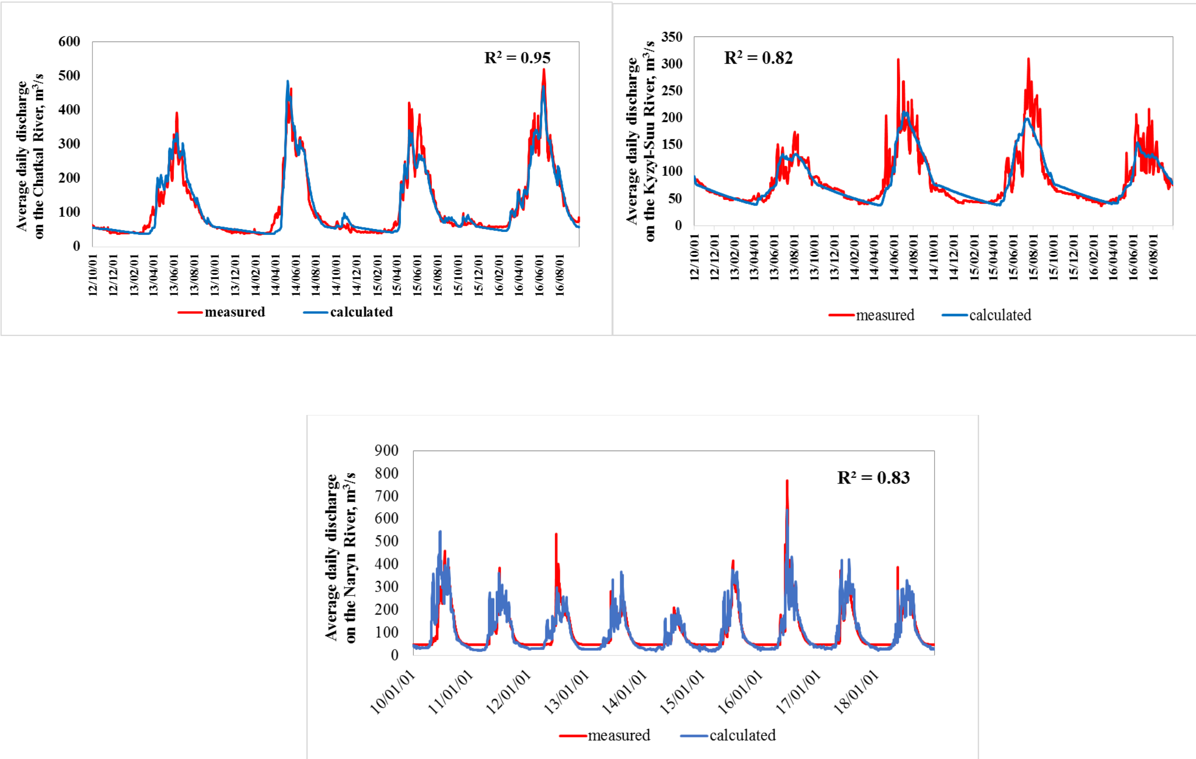


Fig. 7. Calibration of the HBV-light and HBV-EHT models for the Naryn, Chatkal and Kyzyl-Suu river basins

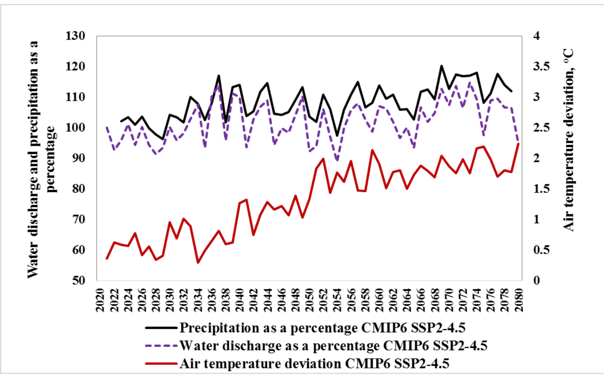
Calculations made using hydrological modeling in key river basins, in accordance with the above climate scenarios, show a gradual increase in the water availability of the rivers of Kyrgyzstan for the period from 2030 to 2080. In the rivers of the northern edge of the Fergana Valley, an increase in the average annual runoff is expected by 1-18%, in the Kyzyl-Suu river - by 27-64% compared to 2006-2019. The exception is the Naryn basin, where the water availability is expected to be within the values of 2006-2019 (Table VI).

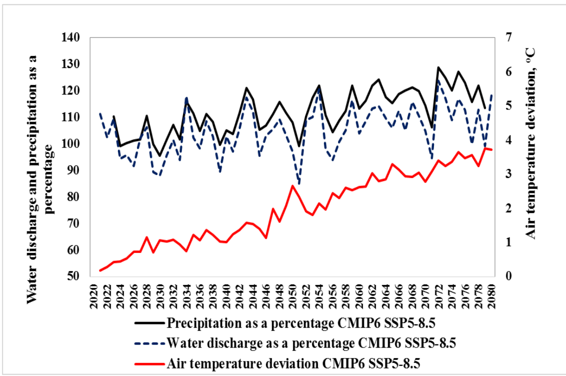
Table VI. Changes in river water availability as a percentage of average values of 2006-2019 according to CMIP5 and CMIP6 scenarios

River / basin	Scenario name	2020-2030	2031-2040	2041-2050	2051-2060	2061-2070	2071-2080
r. Naryn (upper reaches) / tributary to the Toktogul reservoir.	CMIP5 RCP 4.5	91	92	92	95	94	94
	CMIP5 RCP 8.5	94	93	94	98	98	98
r. Chatkal / northern edge of the Fergana valley	CMIP6 SSP2-4.5	101	108	107	107	110	112
	CMIP6 SSP5-8.5	102	106	111	112	119	118
r. Kyzyl-Suu (Amu-Darya river) /	CMIP5 RCP 4.5	127	133	136	144	144	144
	CMIP5 RCP 8.5	130	129	142	151	158	164

Compiled by the author

Combined runoff hydrographs with air temperature and precipitation for snow-glacier and glacier-snow fed rivers, as well as intra-annual runoff variability of CMIP5 and CMIP6 scenarios, obtained from calculations in hydrological models, are shown in Figures 8 and 9.





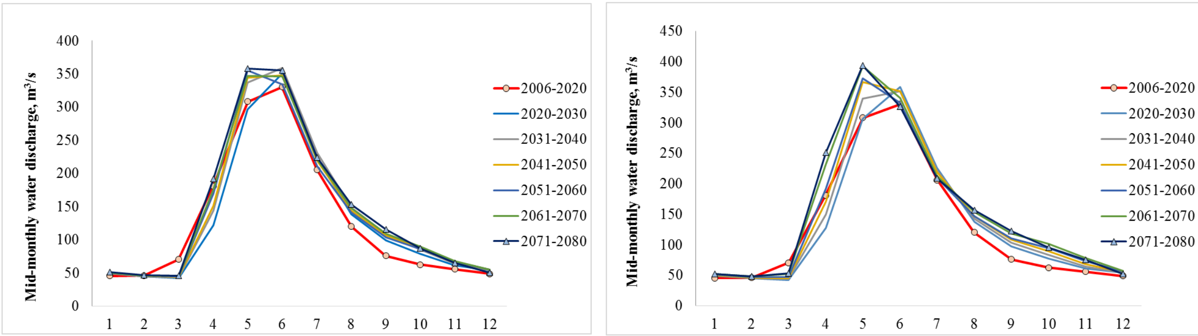


Fig. 8. Inter-annual (top) and intra-annual (bottom) river runoff variability, predominantly snow- fed (snow-glacier fed river type) for example, the Chatkal River. CMIP6 SSP2-4.5 on the left and CMIP6 SSP5.8-5 on the right

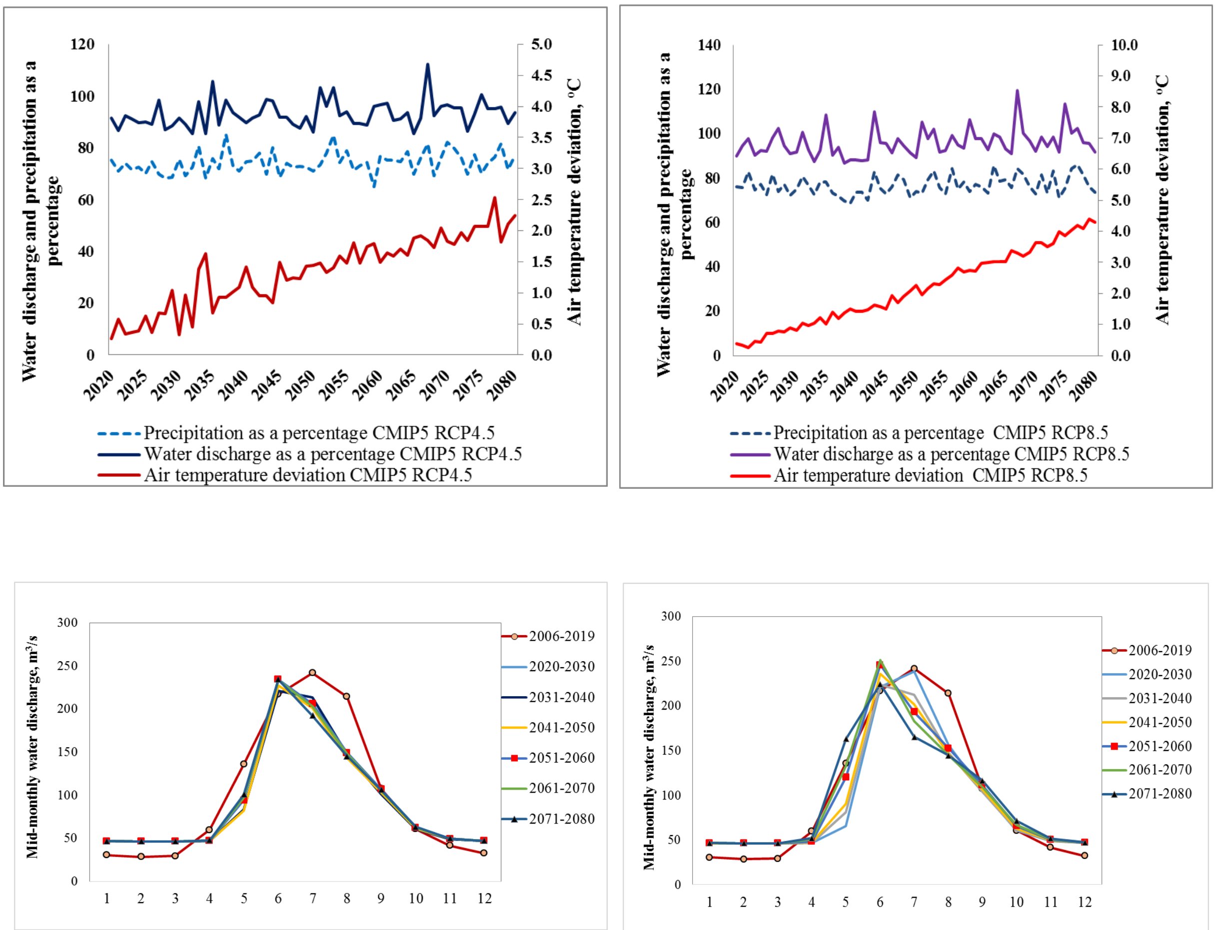


Fig. 9. Inter-annual (top) and intra-annual (bottom) variability of the river runoff, predominantly glacier fed (glacier-snow-fed river type) for example, the Naryn River (upper reaches).. CMIP5 RCP45 on the left and CMIP5 RCP8.5 on the right

The results of the river runoff modeling show that the inter-annual runoff variability and the number of high-water years increase in glacier-snow fed rivers, which is connected with an increase in the share of snowmelt runoff, that depends on precipitation, and which varies significantly and increases from 2040-2050s.

The increase in the water availability of the rivers of Kyrgyzstan is primarily due to increased meltwater from glaciers in high-mountain river basins, where it occupies significant areas of watersheds, as well as an increase in annual precipitation during the cold period, which forms seasonal snow reserves in the mountains.

The intra-annual variability of runoff of snow-glacier-fed rivers, which make up the majority on the territory of Kyrgyzstan, shows an earlier start of seasonal snowmelt and a shift in the peak of water availability to a month earlier - from June to May or the presence of two months with maximum water availability (May and June). In the extreme scenario, water availability of the river in May significantly exceeds water availability of the river in June, and the volume of water also increases in April. In glacier-snow-fed rivers, runoff significantly decreases in August and July, formed by glacier meltwater, and water availability peaks shift from July to June, with an increase in water volume in May in the extreme scenario.

4. Discussion

Many research works are devoted to the issues of water resources assessment of Kyrgyzstan for the future. In 2000, the forecast of changes in the mean annual flow of the rivers of Kyrgyzstan was made by methods of correlation analysis and mathematical statistics (inertial forecast), where it was expected that in 2020 the flow of the rivers of Syr-Darya basin will increase by 10% (including Naryn - by 14%, Kara-Darya - by 3.6%) of values for the observation period 1930 (1940) - 1999 (Mamatkanov et al., 2006).

In the Second and Third National Communications of the Kyrgyz Republic under the UN Framework Convention on Climate Change (SNC and TNC), it was assumed that from 2020-2025 the surface flow of Kyrgyzstan will decrease according to various scenarios. In the SNC (2008), a significant decrease in surface flow to about 42.4 - 20.4 km^3 (43.6 - 88.4 % of the runoff in 2000) was expected for all most possible climate scenarios (Second National Communications of the Kyrgyz Republic under the UN Framework Convention on Climate Change, 2008). In TNC, from 2020-2025 surface flow was also expected to decrease substantially under all possible scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) and under scenarios of changes in precipitation (at historical levels, 5% higher, and 5% lower).At the same time, it was emphasized that “the range of the reduction is very wide”, for the most unfavorable scenario of climate change (RCP8.5 scenario and a decrease in the amount of annual precipitation by 5%), “a decrease in runoff by about 40%” was expected. The maximum flow was also expected to shift to earlier time periods, depending on the elevation of the basin, from 15 to 50 days (Third National Communications of the Kyrgyz Republic under the UN Framework Convention on Climate Change, 2018).

Other results of the Naryn and Kara-Darya basin runoff calculations for 2050 and 2080 using the WASA hydrological model showed that climate change in Central Asia will lead to increased runoff in spring and to its decrease by the end of the growing season (2017). Also the calculations showed different evolution of the area of glaciers in the basins, and in the Kara-Darya basin their disappearance by the 2030s. As a result, it was noted that changes in the flow regime in Central Asian rivers can have a significant impact on future water management, and a decrease in water availability in late summer can lead to water scarcity in agriculture (Gafurov et al., 2017).

According to a recent ADB study on the impacts of climate change on water resources and natural hazards in the Aral Sea Basin, annual surface water flows will increase in the short to medium term, as glaciers melt due to rising temperatures. The study also predicts that annual peak flows are expected to shift from summer to spring and decrease in magnitude and shift precipitation from summer to winter. Irrigation water demand will also increase because of rising temperatures and lower summer rainfall (Final Report Asian Development Bank (ADB) TA8015-REG Kyrgyz Republic, 2013).

The previous studies underscore again the importance of our research, the need to analyze changes in meteorological parameters by 2020, and the development of updated scenarios for changing water resources. Estimation of water availability of rivers for 2030 and 2040 using the method of correlation analysis shows a gradual increase in the flow of rivers in the Syr-Darya and Amu-Darya basins. The least increase of water availability is expected in the Kara-Darya river basin - by 6-8%, and the highest - in the Naryn and Chatkal river basins - by 13-19%, in the Kyzyl-Suu river - by 9-11% of values for 2006-2020.

The effectiveness of the application of the method of correlation analysis (inertial forecast) for a long-term observation period is confirmed by the justification of the forecasts of previous researchers. Thus, the forecasts for 2020 of the Institute of Water Problems of the Academy of Sciences of the Kyrgyz Republic, prepared in 2000 using this method, showed an increase in water availability in the rivers of the Syr-Darya basin by 10% on average; with the Naryn river - by 14%, and the lowest - in the Kara-Darya river - by 3.6% of the values of 1930-2000 (Mamatkanov et al., 2006). In fact, the flow in the Naryn river increased by 15% and in the Kara-Darya river - by 5% of the values for 1930-1999, which corresponds to forecast estimates (see Table 3). The runoff of the rivers of the northern edge turned out to be higher than expected values, which is associated with an underestimation of the amount of precipitation, which, at the time of the forecast, was about and below the long-term average values, and has increased since 2000.

Calculations under scenarios CMIP5 RCP 4.5 and CMIP6 SSP2-4.5, as well as CMIP5 RCP8.5 and CMIP6 SSP5-8.5 for 2020-2080 show the greatest increase in runoff in the Kyzyl-Suu river (Vakhsh river basin, Amu-Darya), which is associated with the presence of heavy glaciation with large glaciers of a complex valley and trough morphological type, as well as an increase in precipitation. The water availability in the snow-glacier fed rivers in the northern edge of the Fergana valley increases at a lower rate, since it depends more on annual precipitation (during the cold period) and less on the melting of glaciers, which have small areas here. In the Naryn river basin, the water availability remains around the values for the period of 2006-2019, which is connected with the application of precipitation scenarios, where they are kept at the level of 70-85% of the current (2006-2019) values.

Within the year flood peaks will shift to earlier dates, on glacier-snow-fed rivers to June and in snow-glacier-fed rivers to May.

The results obtained from the calculations carried out for the preparation of scenarios for changes in water resources in the future do not contradict the results of the authors who conducted studies using modeling for the rivers of the Syr-Darya and Amu-Darya basins. As in our study, according to the CMIP5 scenarios, the annual runoff in the Vakhsh river is expected to increase by 17.5-52.3% of the mean long-term values by the end of the century (2099) (Gulakhmadov et al., 2020). Similar shifts in flood peaks and an increase in water availability during the months of seasonal snowmelt have been projected by other researchers (Gafurov et al., 2017; Duethmann et al., 2016; Hagg et al., 2006). Besides the Syr-Darya basin, studies that were carried out in the upper reaches of the Amu-Darya show a similar pattern with a shift in flood peaks from summer to spring. The scenarios showed a slight decrease in annual runoff, as the decrease in glacier area is almost offset by an increase in the rate of melting. Seasonal shifts in water resources will adversely affect agriculture and irrigation in the lowlands of Central Asia (Hagg et al., 2013).

As for the reduction of water availability related to the depletion of glacier feeding, opinions differ here: some researchers point to a decrease in runoff after the 2040s and to the shift of flood peaks in the highlands of the Tien Shan, others believe that in the coming decades, the contribution to runoff from melting glaciers will increase and the transition from glacier-nival to nival-pluvial runoff regime will occur no earlier than at the end of this century (Duethmann et al., 2016; Hagg et al., 2018). The area of these studies requires further development.

Opposing results were presented in the SNC and TNS, where river flows were expected to decrease from 2020-2025 due to a decrease in glacial runoff. A decrease or increase in precipitation by 5% of the mean annual values were considered in the results of the calculations. In general, the annual amount of precipitation in the rivers of the south of the republic (Fergana Valley) increased by 12%, and in the period 1976-2017 by 20% of the long-term observation period. In the high-mountain area, the shift of flood peaks was expected 50 days earlier, which also does not coincide with the results of our study.

Hydrological modeling is a rather flexible tool with various options of calculation results. However, it is necessary to choose climate scenarios carefully, because rivers are the product of climatic factors.

5. Conclusion

Of great practical (water management and hydropower) importance is the glacial runoff of the river in July and August, when the irrigation water is usually needed most and the reservoirs should be filled during the warm season to generate electricity. Increased water flow of rivers in spring time, in April and May, when there are frequent incursions of moist northern and northwestern air masses, especially in mountainous areas open towards the moist-carrying masses (northern edge of Fergana Valley) will lead to increased mudflow and flooding. An increase in the number of glacial moraine lakes due to the melting of large glaciers and the formation of small independent glaciers will increase the threat of catastrophic mudflows caused by outburst lakes. Among of the most vulnerable river basins are small high-altitude watersheds, as unlike large water-bearing rivers, they are more susceptible to climate changes associated with frequent changes in weather conditions. Major basins, such as the Tarim river basin and the Kyzyl-Suu (western) river, with a significant area of heavy glaciation, have uncertainty due to the period, when the glacial runoff reaches its critical values. There is no reliable information about how water availability in such watersheds will change, and whether the flow will decrease only in summer, or, with a deficit of precipitation during the cold period, the water availability of these rivers will significantly decrease.

Recommendations for decision makers:

- to take bank protection and mudflow prevention measures in a timely manner in order to prevent and reduce the consequences of mudflow and flood hazards;
- to strengthen monitoring of river flows and to establish early warning systems for sudden rises in water levels and the risk of floods;
- it is necessary to conduct a preliminary hazard assessment with an engineering-geological approach;
- it is necessary to carry out activities on increasing awareness, knowledge and capacity for effective response, as well as competent self-protection of the population (local communities) of vulnerable areas from natural disasters;

- in connection with the reduction of water availability in rivers in summer, it is recommended to build reservoirs and basins of daily (ten-day) regulation;

- it is necessary to build scientific and educational capacity to develop reliable scenarios for the changes in the river water availability under global climate warming.

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Annex 1. List of global climate models of the international project CMIP6

No	Model	Institute-developer of the model	Resolution (longitude-latitude), degrees
1	ACCESS-CM2	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), ARCCSS (Australian Research Council Centre of Excellence for Climate System Science)	1.875x1.25
2	ACCESS-ESM1-5	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia)	1.875x1.25
3	AWI-CM-1-1-MR	The Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Germany	0.938
4	BCC-CSM2-MR	Beijing Climate Center, China	1.125
5	CAMS-CSM1-0	Chinese Academy of Meteorological Sciences, China	1.125
6	CESM2-WACCM	National Center for Atmospheric Research, Geophysical Fluid Dynamics Laboratory, USA	1.25x0.94
7	CIESM	Department of Earth System Science, Tsinghua University, China	1.25
8	CanESM5	The Canadian Center for Climate Modelling and Analysis, Environment and Climate Change, Canada	2.8125
9	EC-Earth3	EC-Earth consortium, European Union	0.703
10	EC-Earth3-Veg		
11	INM-CM4-8	Institute of Computational Mathematics, Russian Academy of Sciences, Russia	2x1.5
12	INM-CM5-0		
13	FGOALS-f3-L	Chinese Academy of Sciences, China	1.25x1
14	FGOALS-g3 2		2
15	FIO-ESM-2-0	FIO (First Institute of Oceanography, Ministry of Natural Resources, China), QNLM (Qingdao National Laboratory for Marine Science and Technology, China)	1.25x0.94
16	GFDL-ESM4	National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, USA	1.25
17	IPSL-CM6A-LR	Pierre Simon Laplace Institute, France	2x1.268

18	KACE-1-0-G	National Institute of Meteorological Sciences / Korea Meteorological Administration, Weather Research Department, Republic of Korea	1.875x1.25
19	MIROC6	JAMSTEC (Japan Agency for Marine-Earth Science and Technology, Japan), AORI (The Atmosphere and Ocean Research Institute, the University of Tokyo, Japan), NIES (The National Institute for Environmental Studies, Japan), and R-CCS (RIKEN Center for Computational Science, Japan)	1.406
20	MPI-ESM1-2-HR	The Max Planck Institute for Meteorology, Germany; Germany's National Meteorological Service, Germany; The German Climate Computing Centre, Germany	0.938
21	MPI-ESM1-2-LR	The Max Planck Institute for Meteorology, Germany; Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Am Handelshafen 12, 27570 Bremerhaven	1.875
22	MRI-ESM2-0	Meteorological Research Institute, Japan	1.125
23	NESM3	Nanjing University of Information Science and Technology, China	1.875
24	NorESM2-LM	The NorESM Climate modeling Consortium consisting of CICERO (Center for International Climate and Environmental Research, Oslo, MET-Norway (Norwegian Meteorological Institute, Oslo), NERSC (Nansen Environmental and Remote Sensing Center, Bergen), NILU (Norwegian Institute for Air Research, Kjeller), UiB (University of Bergen, Bergen), UiO (University of Oslo, Oslo) и UNI (Uni Research, Bergen), Norway.	2.5x1.89
25	NorESM2-MM 1.25x0.94		1.25x0.94