



Attribution of current trends in streamflow to climate change for 12 Central Asian catchments

Iulii Didovets¹ · Valentina Krysanova¹ · Aliya Nurbatsina² · Bijan Fallah¹ · Viktoriya Krylova³ · Assel Saparova² · Jafar Niyazov⁴ · Olga Kalashnikova⁵ · Fred Fokko Hattermann¹

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Abstract

This study investigates the attribution of climate change to trends in river discharge during six decades from 1955 until 2014 in 12 selected river catchments across six Central Asian countries located upstream of the main rivers. For this purpose, the semi-distributed eco-hydrological model SWIM (Soil and Water Integrated Model) was firstly calibrated and validated for all study catchments. Attributing climate change to streamflow simulation trends was forced by factual (reanalysis) and counterfactual climate data (assuming the absence of anthropogenic influence) proposed in the framework of the ISIMIP (Inter-Sectoral Impact Model Intercomparison Project) or ESM without anthropogenic forcing that were firstly tested and then compared. The trend analysis was performed for three variables: mean annual discharge and high flow (Q5) and low flow (Q95) indices. The results show that trends in the annual and seasonal discharge could be attributed to climate change for some of the studied catchments. In the three northern catchments (Derkul, Shagan, and Tobol), there are positive trends, and in two catchments (Sarysu and Kafirnigan), there are negative streamflow trends under the factual climate, which could be attributed to climate change. Also, our analysis shows that the average level of discharge in Murghab has increased during the historical study period due to climate change, despite the overall decreasing trend during this period. In addition, the study reveals a clear signal of shifting spring streamflow peaks in all catchments across the study area.

Keywords Climate change · Trend detection · Attribution to climate change · Central Asia · Hydrological modelling · Water availability · River discharge · SWIM · Amu Darya · Syr Darya

1 Introduction

Climate change affects the water cycle through changes in precipitation, atmospheric moisture, and evapotranspiration. It leads to changes in general water availability, seasonality, and extremes like floods or droughts in terms of frequency and intensity (IPCC 2021).

During the last five decades, global mean temperature has increased to an exceptional level at least for the past 2000 years (IPCC 2021). The global temperature for the period

from 2001 to 2020 is 0.99 °C higher compared to the period from 1850 to 1900. The observed warming since the mid-twentieth century is larger than the internal variability on the 60-year time scale estimated by climate models. It confirms that internal variability alone including natural factors like solar activity or volcanic eruption cannot solely be attributed to the observed global warming since 1951 (IPCC. 2014; IPCC 2021).

The Central Asian region (CA) has experienced a significant increase in temperature, higher than the global average (Vakulchuk et al. 2023). Changes in climate parameters like temperature and precipitation and further changes in water parameters during the last decades have been confirmed by different studies with a focus on the Central Asian region.

For example, the study by Haag et al. (2019) showed an increasing trend in temperature across the Central Asian region with acceleration from the 1990s. Similar tendencies have been observed by other authors showing a temperature rise of 0.36–0.42°C/10 years for the period from 1979 to 2011 (Hu et al. 2014), 0.20°C/10 years since 1950 in the paper of Siegfried et al. (2012), and from 0.6 to 1.2°C on average from 1950 to 2001 (Savitskiy et al. 2008). Notably, some studies indicate a temperature increase in the mountainous regions of CA, e.g., from 1960 to 2015 in Tien Shan (Chen et al. 2018; Sorg et al. 2012), and in Pamir-Alay (Chevallier et al. 2014). At the same time, the study by Savitskiy et al. (2008) analyzed changes in temperature from 40 meteorological stations located in the mountains for the period from 1950 to 2001 and found that 90% of them have only a small temperature increase. Changes in observed precipitation over recent decades have shown ambiguous tendencies. There are regional variations in the signals of change, their intensity, and significance (Sorg et al. 2012; Haag et al. 2019; Yao et al., Yao and Chen 2015). In the study by Haag et al. (2019), the authors analyzed precipitation trends from 1950 to 2016, primarily in mountainous areas (from 35° to 45° N and from 65° to 80° E). Their results did not indicate any significant long-term statistical trend. However, the study by Yao et al. (2015), focusing on the Syr Darya Basin, identified a significant rising trend of 4.44 mm/year. Furthermore, the research by Chen et al. (2011), based on CRU data from 1930 to 2009, revealed a general rising trend in annual precipitation across the study region, with the exception of the southwestern part.

Changes in river discharge vary between the regions and feeding sources. Some studies indicate an increase of streamflow in highly glacierized catchments, e.g., in Kyrgyzstan, where the long-term mean discharge increased from 47 to 50 km³ in the period 1973–2000 in comparison to 1947–1972 (Sorg et al. 2012). However, there are no significant trends or negative trends found in other catchments (Savitskiy et al. 2008; Agal'tseva et al. 2011; Wang et al. 2019). Nevertheless, several papers confirmed seasonal changes in river discharge with alteration in spring months, and, as a result, shifting of floods peak to an earlier period and decrease of streamflow in summer months (Chevallier et al. 2014; Chen et al. 2018).

There are several studies which investigate the future climate change impacts on water resources in the Central Asian region by employing different climate and hydrological models driven by RCP scenarios (Agal'tseva et al. 2011; Ayzel and Izhitskiy 2018; Haag et al. 2019; Didovets et al. 2021; Kalashnikova et al. 2023). The key findings include increase in runoff for small glacierized headwater catchments in mountains, decrease in river discharge for many tributaries of Amu Darya and Syr Darya rivers, and increase in streamflow for some rivers in the northern part of Kazakhstan, whereas magnitudes of both negative and positive change signals are rising from mid-century to far future and from lower RCPs to the high-end RCP8.5. Besides, these studies show that the rising temperature leads to earlier snowmelt and shifting of spring flood peaks to an earlier period (up to 1 month) in many Central Asian rivers.

Detection of trends and their attribution provide a critical framework for understanding and addressing challenges associated with climate warming. There are studies on impact attribution to climate change comparing observed dynamics of river discharge with simulated time series driven by detrended climate data describing system behavior without climate change (Hundechea and Merz 2012; Trambly et al. 2019), as well as studies comparing hydrological system behavior driven by anthropogenically forced climate model outputs and so-called natural climate model outputs excluding human forcing (Huang et al., 2018; Hirabayashi et al., 2021; Gudmundsson et al., 2021; Gelfan et al., 2023). Based on the identification of factors driving changes in the climate and hydrological systems provided by science, policymakers and stakeholders can develop more effective mitigation and adaptation strategies to ensure the sustainable development and security of the region. However, to the best of our knowledge, there are no similar studies for Central Asia on attribution of the observed changes in river discharge, seasonality, and hydrological extremes during the last decades to climate change.

In this study, we focus on the detection of trends in river discharge and their attribution to climate change for 12 river catchments in Central Asia. The main goal of this paper is to understand whether and how water resources in terms of mean annual discharge and seasonal high and low flows were affected by climate change over the last six decades. For this purpose, the calibrated and validated Soil and Water Integrated Model (SWIM) was driven by the factual and counterfactual climate datasets from the ISIMIP project (Inter-Sectoral Impact Model Intercomparison Project) to simulate river discharge, and the simulated time series were analyzed for trends and compared. If the trend under the factual climate is statistically significant and the trend under the counterfactual climate is not, then the former one could be attributed to climate change. Additionally, various climate inputs including ESMs runs (natural and historical) were tested for attribution.

2 Study area

For the assessment of climate change and attribution to trends in streamflow, 12 river catchments were selected across Central Asia (Fig. 1). The catchments are located in different climate zones, vary in size, and have different flow regimes (from nival to nivoglacial and glacial-nival). Six of them are located in Kazakhstan (Derkul, Shagan, Tobol, Zhabay, Sarysu, and Bukhtarma) partly sharing the drainage areas with Russia or China. Five catchments (Zeravshan, Isfara, Tupalang, Vakhsh, and Kafirnigan) are located in the central part of the study region and originate in the high mountains. Most of them are lying in Tajikistan and partly in Uzbekistan or Kyrgyzstan. Four catchments (Zeravshan, Tupalang, Vakhsh, and Kafirnigan) belong to the Amu Darya basin and Isfara—to the Syr Darya basin. The 12th catchment, Murghab, is located in the southern part of the domain. The river originates in the mountains of Afghanistan and flows to Turkmenistan.

The Shagan River is a right tributary of the Zhaiyk River; it is 264 km long and its total catchment area of 7530 km² is located in the north-western part of Kazakhstan. Together with its right tributary Derkul River (176 km long and catchment area of 2200 km²), it is mainly snow fed with a streamflow peak in spring, low flow in summer–autumn, and frozen in winter time (Hydrometizdat 1970, Natural conditions and resources 2007; Galperina 2012). The average annual air temperature of the Shagan River basin is 5.0 °C, the average annual relative humidity reaches 72%, and the average annual precipitation is 300–380 mm. The Zhabay, Tobol, and Bukhtarma River catchments belong to the Ertis



Fig. 1 Twelve river catchments under study

(further downstream called Irtysh after crossing the border to Russia) River basin. All three catchments are located in cold climate conditions where the annual mean temperature varies from -3.2 to 3.3 °C. The catchments are mainly fed by snow and rain. Annual precipitation varies from 330 mm in Tobol to 612 mm in the Bukhtarma catchment. In the Zhabay and Tobol catchments, the range between minimum and maximum altitudes within the catchment does not exceed 500 m, and the average elevation of Bukhtarma is around 1500 m (Hydrometizdat 1966; Didovets et al. (2021).

The Sarysu River originates in the Kazakh uplands and flows through arid areas of semi-desert and desert. The total length of the river is 761 km, and the catchment area is 81,600 km². The river is characterized by irregular flow distribution in time. The surface runoff in the catchment is insignificant in summer, and the Sarysu dries up for most of its length. In most parts of the catchment area, the average annual precipitation varies from 100 to 155 mm (Hydrometizdat 1966).

The five tributaries of the Amu Darya and Syr Darya are mainly snow and glacier-fed with an average catchment altitude above 1700 m. The average annual temperature varies from 3.1 to 7.1 °C, and the average annual precipitation from 405 mm in Tupalang to 677 mm in Kafirnigan with the highest values in spring. All rivers under study have strong streamflow seasonality with high peaks in the spring–summer period, depending on the flow regime (Shults 1965). The impacts of different natural aspects on the hydrological cycle have been discussed by Didovets et al. (2021).

The most southern river catchment in this study, Murghab, with 850 km river lengths and a total catchment area of 46,880 km² originates in Paropamisus Mountains and flows into the Karakum Desert. The mean annual temperature in the catchment is 12.8 °C, and annual precipitation is 308 mm with the highest values from February to March (Didovets et al. 2021).

The drainage areas of all 12 river catchments are located upstream of large rivers and have a predominantly natural flow. They are practically not influenced by water management: there are no reservoirs or water-dependent industries above the considered gauge stations. The only exception is the Murghab basin having irrigated agriculture fields in Afghanistan. However, due to a lack of observational data and very limited open data about the region, it was impossible to consider this during the modelling.

3 Methods

The current study was implemented in three steps involving (1) calibration and validation of the hydrological model for all study areas; (2) running the hydrological model forced by climate data representing factual climate assuming anthropogenic influence (reanalysis or earth system model, ESM), as well as by climate data assuming the absence of anthropogenic influence (detrended reanalysis or ESM without anthropogenic forcing); and (3) trend analysis of climate input time series and all model outputs and their comparison (Figure 2). In the first stage, the SWIM was set up, calibrated, and validated for 12 river catchments in Central Asia. After that, the model was run driven by reanalysis and ESM climate data for the historical period (1955–2014) as well as by the detrended reanalysis data and ESM without anthropogenic forcing. This framework for climate attribution studies and all

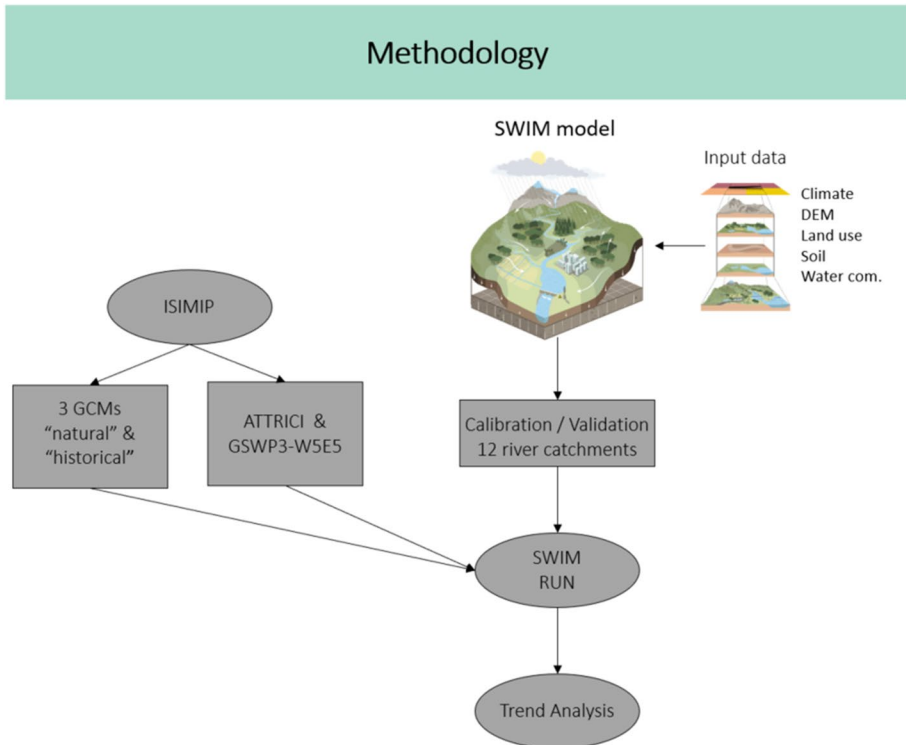


Fig. 2 Methodology of the study

climate input data were provided by the ISIMIP project (ISIMIP 2023). The corresponding simulation protocols ISIMIP3a and ISIMIP3b can be found at <https://protocol.isimip.org/>. The trend analysis was performed for three variables: mean annual discharge, high flow (Q5) indices, and low flow (Q95) indices. The advantage of using these three variables in comparison with using only mean annual streamflow is that the analyses of trends in mean streamflow and extremes allow to get a full pattern of trends under the factual and counter-factual climates. The high flows are driven by snow/glacier melt or intensive precipitation, and low flows correspond to periods with high temperature (and high evapotranspiration) combined with low or no precipitation. While trends in high flows (Q5) approximate trends in floods, trends in low flow index Q95 approximate modifications in droughts. The simulated discharge, low flow indices, and high flow indices were analyzed for trends together with climate variables.

3.1 Hydrological model setup, calibration, and validation

The SWIM model (Krysanova et al. 2000) applied in this study is a semi-distributed, continuous-time ecohydrological model that integrates hydrological processes, vegetation growth, sediment transport, and nutrient cycling. The model uses a three-level spatial disaggregation scheme (basin, sub-basins, and hydrological response units) and operates on a daily time step. The model has been successfully used to study various climate change-related issues, including extreme events and water quality, and applied in numerous river basins worldwide (Hattermann et al. 2014, Hatterman et al. 2018, Huang et al. 2013; Krysanova et al. 2015; Liersch et al. 2017; Didovets et al. 2019).

The model was set up for each river catchment separately based on different types of data, such as digital elevation model, land use, soil map and soil profile parametrization, and climate data (daily min, max and mean temperatures, precipitation, solar radiation, and relative air humidity). Detailed information about the input data is presented in Table 1. SWIM has been already calibrated/validated for seven river catchments (Zhabay, Bukhtarma, Zeravshan, Isfara, Tupalang, Murghab, and Kafirnigan), and used for climate impact assessment in the previous study (Didovets et al. 2021). However, due to the application of an updated version of SWIM and different climate-driving data from several sources, new model setups and recalibrations were done for this study.

Table 1 Input data used for the hydrological modelling

Data type, variable	Dataset	Resolution	Reference
Air temperature, precipitation, air humidity, solar radiation	GSWP3, W5E5, observations	0.5 degree	(ISIMIP 2023)
Digital elevation model (DEM)	SRTM	90 m	(CGIAR-CSI 2023)
Land use	Globeland30	30 m	(Chen et al. 2015)
Soil map and parameters	HWSD	1000 m	(FAO 2012)
Climate projections/models	GSWP3-W5E5, ATTRICI, MRI-ESM2-0*, IPSL-CM6A-LR*, GFDL-ESM4*	0.5 degree	(ISIMIP 2023)
Glacier ice thickness	GLIMS	500 m	(RGI Consortium 2017)

*For every three ESMs, two time series were applied: “historical” and “natural” (see explanation below)

For model calibration and further validation, the observed daily and/or monthly river discharge data were obtained from different sources, such as the GRDC database (GRDC 2023), Hydromet services in Central Asian countries, and local institutions. Due to a lack of observations in some years and missing values in some time series, the calibration and validation periods were established separately for each river catchment.

3.2 Climate data

As can be seen in Table 1, several climate datasets from the ISIMIP project (ISIMIP 2023) were used to run the hydrological model SWIM for detecting trends and analyzing the contribution of climate change to the trends in streamflow. The first dataset includes the following:

- a) The “observational dataset” GSWP3-W5E5 which is a combination of the Global Soil Wetness Project Phase 3 (GSWP3) dataset v1.09 (1901–1978) and W5E5 v2.0 (1979–2019), which was homogenized at the daily temporal scale and 0.5 spatial resolution (further called “factual”).
- b) ATTRICI v1.1 counterfactual climate data which was derived from the observational dataset GSWP3-W5E5 for the period from 1901 to 2019 by detrending, thus representing climate data without climate trend (further called “counterfactual”). The method identifies the long-term shifts in the considered daily climate variables that are correlated to global mean temperature change. In addition, it preserves the internal variability of the observed data in the sense that factual and counterfactual data for a given day have the same rank. As a result, the associated impact model simulations allow for quantifying the contribution of climate change to observed long-term changes in impact indicators and for quantifying the contribution of the observed trend in climate to the magnitude of individual impact events. More information about the ATTRICI data can be found in Mengel et al. (2021).

The second dataset applied for climate trend attribution was taken from ISIMIP3b and represents bias-corrected CMIP6 climate forcing at the daily time step with 0.5 spatial resolution. In our study, three ESMS (earth system models: MRI-ESM2-0, IPSL-CM6A-LR, and GFDL-ESM4) were used (Lange 2019; Lange et al. 2021; ISIMIP 2023). The second dataset includes the following:

- (a) Model runs of three ESMS called “historical,” i.e., with anthropogenic and natural forcing (further “factual”).
- (b) Model runs of three ESMS called “natural,” meaning the model runs without anthropogenic forcing (further “counterfactual”).

The bias correction was done to W5E5 and is described in Lange et al. (2021). The period for the analysis was from 1955 to 2014.

3.3 Trend analysis of time series

For the analysis of simulated river discharge and comparison of outputs driven by factual and counterfactual climate scenarios, trend analysis of all obtained time series was conducted. The nonparametric Mann–Kendall (MK) test for trend detection (Mann

1945; Kendall 1948) together with the Theil-Sen (Sen 1968) method to detect the direction and slope of changes was applied to the annual river discharge, as well as to annual time series of high and low flows. The MK test is one of the rank-based methods used to detect the significance of trends in the time series (Hamed 2008; Wang et al. 2020). Both methods are widely used in hydrological science for streamflow, lake level, groundwater, lake level analysis, etc. (Wang et al. 2020; Frollini et al. 2021). To avoid the influence of serially correlated data, the modified Mann–Kendall test proposed by Yue and Wang (2004) was applied.

4 Results

4.1 Hydrological model calibration and validation

Table 2 and Fig. 3 illustrate the results of the SWIM model calibration/validation. Table 2 provides criteria of fit and some additional information for 12 catchments, and Fig. 3 shows graphs comparing daily and seasonal dynamics of the observed and simulated river discharges in the calibration and validation periods in four catchments. The calibration/validation results for the rest eight catchments (seasonal dynamics) are presented in Supplementary materials (Fig. S1). The model calibration was performed manually for each catchment due to variations in discharge data availability (daily or monthly) and different periods of available data. Thus, the SWIM model was calibrated and validated separately for each river catchment. In some catchments, the observation period was limited to 5–6 years only, so it was decided to use the whole time series for the model calibration.

The model performance was evaluated by calculating NSE and PBIAS criteria for both periods. The calibration results for most of the catchments could be rated from “satisfactory” to “very good” according to the classification system proposed by Moriasi et al. (2015). However, some results in terms of criteria showed too low NSE (Derkul in the validation period, Murghab in the calibration period) or too high PBIAS (Derkul and Tobol in both periods). In the Murghab catchment, this can be attributed to unaccounted water abstraction for irrigation upstream of the gauging station. Another two catchments are characterized by irregularity of river flow during the year, especially in the summertime, and this could influence the model performance.

The calibration process emphasized the importance of the snow and routing processes, and parameters describing those as the most crucial calibration parameters for all study regions. Furthermore, a glacier module was incorporated in the mountainous catchments which have glaciers; and this resulted in improved model performance. The glacier module applies a degree-day method to simulate daily glacier melt and glacier water accumulation.

4.2 Analysis of climate input data

After the SWIM model calibration and validation, the river discharge was simulated for the period from 1955 to 2015 driven by the factual and counterfactual data from the two datasets based on detrended GSWP3-W5E5 data and ESM simulations (MRI-ESM2-0, IPSL-CM6A-LR, GFDL-ESM4) with and without climate forcing. Dynamics of the mean annual

Table 2 Main characteristics of the catchments

Num	Basin	Country	Gauging station	Modelled area, km ²	Annual P, mm	Mean annual T, °C	Time period	NSE	PBIAS
1	Derkul	KZ	Beles	1924	367	5.7	Calibration 1981–1984 Validation 1985–1988	0.81	62
2	Shagan	KZ, RU	Chuvashynskoe	4487	400	5.5	Calibration 2008–2012 Validation 2013–2017	0.91	12
3	Tobol	KZ, RU	Grishenka	13674	330	3.3	Calibration 2001–2007 Validation 2008–2012	0.73	45.9
4	Zhabay	KZ	Atbasar	8530	426	2.9	Calibration 2001–2006 Validation 2008–2013	0.73	33
5	Sarysu	KZ	Kyzylzhar	34615	200	3.6	Calibration 2013–2017 Validation 2002–2007	0.87	–12.2
6	Bukhtarma	KZ	Lesnaya-Pristan	10700	612	–3.2	Calibration 2008–2012 Validation 1963–1980	0.84	–12.3
7	Isfara	TJ, KG	Tash-kurgan	3200	440	6.4	Calibration 1981–1991 Validation 1981–1985	0.68	8.8
8	Zeravshan	TJ, UZ	Dupuli	102,00	451	3.8	Calibration 1986–1990 Validation 1981–1986	0.91	2.3
9	Kafirnigan	TJ	Chinor	3216	677	5.3	Calibration 1987–1990 Validation 1981–1984	0.81	0.2
10	Vakhsh	TJ	Komsomolobad	38514	530	3.1	Calibration 1985–1988 Validation 1961–1976	0.86	–1.5
11	Tupalang	TJ, UZ	Obizarang	2630	405	7.1	Calibration 1977–1989 Validation 2008–2013	0.9	7.3
12	Murghab	AF, TM	Tagtabazar	35963	308	12.8	Calibration 2008–2013	0.89	12.9
								0.75	–15
								0.79	–1
								0.44	1.6

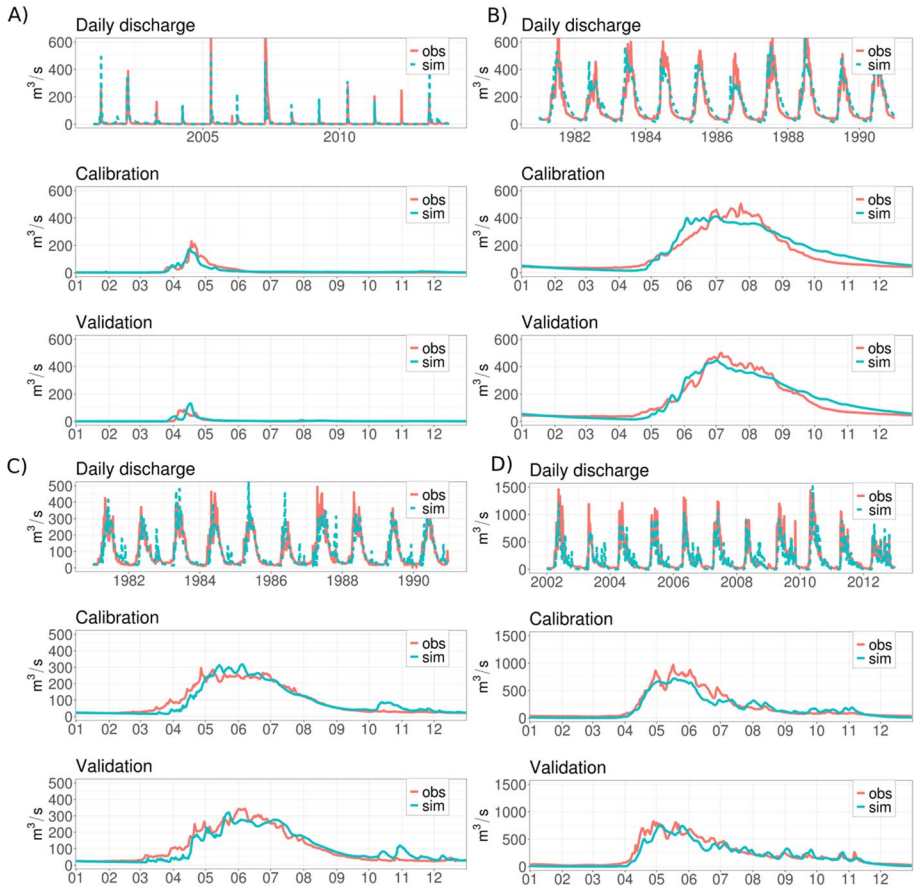


Fig. 3 Results of the SWIM model calibration and validation in **A** Zhabay, **B** Zeravshan, **C** Kafirnigan, **D** Bukhtarma: comparison of the observed and simulated daily river discharges for the long-term mean daily dynamics over the calibration and validation periods

air temperature show a clear increasing signal in all the factual climate datasets compared to the counterfactual, where trends are missing (Figs. 4 and 5). Dynamics of precipitation in the factual and counterfactual data do not show consistent trends across all catchments and depend on river catchment and climate data source (see Fig. 6, upper row).

Moreover, during the comparison of datasets based on GSWP3-W5E5 and outputs from ESMs, it was found that the latter has an underestimation of annual precipitation in several catchments. The deviation is especially strong in the mountainous regions which are important as the main areas of accumulation of river discharge. For example, Fig. 4 shows the mean annual precipitation for the Vakhsh catchment in the period 1980–2014 based on W5E5 and GFDL-ESM4. As one can see, the GFDL-ESM4 model shows an underestimation of annual precipitation (361 mm/year) by 34% across the catchment in comparison with the W5E5 data. Such kind of deviation can provoke notable effects on river discharge and would be a significant source of uncertainty. Taking this into account, we decided to exclude results driven by ESMs from the main analysis in the paper and to use them only as additional information (the ESM-based results are placed in SM. Figs. S5, S6, S7).

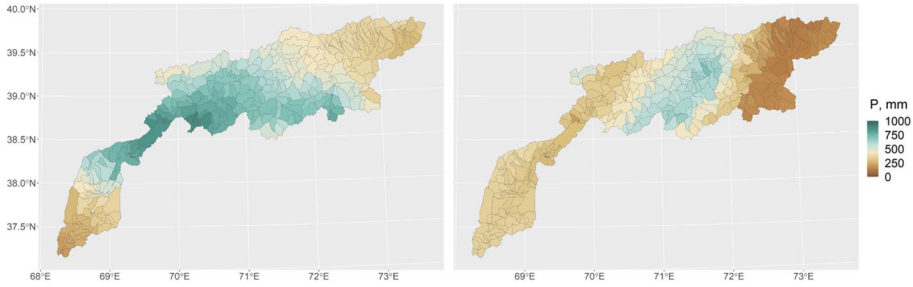


Fig. 4 Annual mean precipitation in the Vakhsh River catchment at the sub-basin level for the period from 1980 to 2014 based on W5E5 (left) and GFDL-ESM4 historical runs (right)

Rivers	Counterfactual			Factual		
	Mean	Q5	Q95	Mean	Q5	Q95
Derkul	-0.009	-0.022	-0.001	0.027 *	0.052 *	0.025 *
Shagan	0.002	-0.011	0	0.051 *	0.165 *	0.0004 *
Tobol	-0.007	0.057	0.004	0.029	0.272 *	0.009 *
Zhabay	0.069 *	0.484 *	0.003 *	0.084 *	0.576 *	0.004 *
Sarysu	-0.001	0.013	-0.006	-0.036 *	0.049	-0.005
Bukhtarma	0.035	0.641	0.001 *	0.063	-0.298	0.003 *
Isfara	-0.029	-0.062	-0.005 *	-0.012	-0.012	-0.007 *
Zeravshan	-0.229 *	-0.714 *	-0.035 *	-0.362 *	-0.885 *	-0.042 *
Kafirnigan	-0.088	-0.126	-0.027 *	-0.154 *	-0.276 *	-0.055 *
Vakhsh	-0.866 *	-1.61 *	-0.461 *	-1.088 *	-3.142 *	-0.707 *
Tupalang	-0.03 *	-0.079 *	-0.014 *	-0.026	-0.153 *	-0.009
Murghab	-0.436 *	-0.955 *	-0.181 *	-0.317 *	-0.792 *	-0.061 *

Fig. 5 Annual river discharge trends (mean, Q5, Q95) for factual (left) and counterfactual (right) climates over 12 river catchments for the period from 1955 to 2014. * indicates a significant trend, numbers and colors display Sen’s slope

4.3 River discharge trend analysis

Figure 5 presents results on trends in the annual river discharge based on factual (GSWP3-W5E5) and counterfactual (ATTRICI) data for 12 study catchments focusing on annual mean, low flow (Q95) and high flow (Q5). The statistically significant trends ($p=0.05$) are marked by stars and positive and negative Sen’s slopes by blue and red colors, respectively. As the slopes are in absolute units, they depend on the mean discharge of the catchment, and cannot be compared between basins. Below under “trend was found”, we mean that “statistically significant trend was found.”

4.3.1 Trends in mean annual discharge

Positive trends in mean discharge under the factual climate were found for three northern catchments: Derkul, Shagan and Zhabay; and for the first two, they disappeared under the counterfactual climate. Negative trends in mean discharge under the factual climate could be identified for Sarysu and four southern catchments, Kafirnigan, Zeravshan, Vakhsh and Murghab, and for the last three, the negative trends were maintained

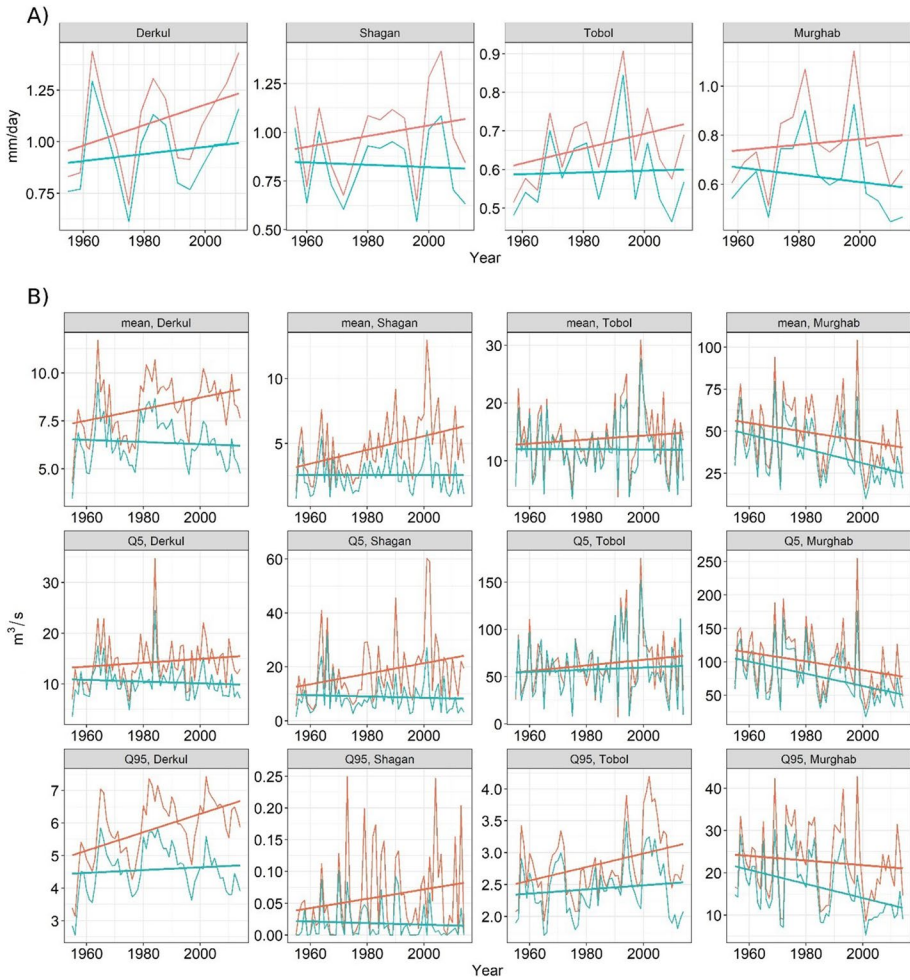


Fig. 6 Annual precipitation (A), and river discharge mean, Q5, Q95 (B) in the Derkul, Shagan, Tobol, and Murghab catchments driven by factual (red) and counter-factual (blue) datasets

under the counterfactual climate. There were no significant trends found under both climates for Tobol, Bukhtarma and Isfara, whereas for Tupalang, both negative trends have similar slopes, but only the trend under the counterfactual climate is statistically significant. The visual comparison of trend lines (Fig. 6, Fig. S2) suggests that there are three catchments from 12 with notable differences in trends under two climates: Derkul, Shagan and Murghab. Though both trends for the Murghab are negative, the mean levels of discharge differ substantially, with the higher level under the factual climate.

4.3.2 Trends in low flow, Q95

Positive trends in Q95 under the factual climate were found for five northern catchments, Derkul, Shagan, Tobol, Zhabay, and Bukhtarma, and for the first three, they disappeared

under the counterfactual climate. Negative trends in Q95 under the factual climate could be identified for Isfara, Kafirnigan, Zeravshan, Vakhsh and Murgab, and all five also negative trends were found under the counterfactual climate. There were no significant trends found under both climates for Sarysu, whereas for Tupalang, both negative trends have similar slopes, but only the trend under the counterfactual climate is statistically significant. The visual comparison of trend graphs (Fig. 6, Fig. S2) suggests that there are five catchments from 12 with essential differences in Q95 trends under two climates: Derkul, Shagan, Tobol, Bukhtarma and Murghab. The same as for mean discharge, both Q95 trends for the Murghab are negative, but the levels of trend lines differ substantially, with the higher level under the factual climate.

4.3.3 Trends in high flow, Q5

Positive trends in Q5 under the factual climate could be found for four northern catchments, Derkul, Shagan, Tobol and Zhabay, and for the first three, they disappeared under the counterfactual climate. Negative trends in Q5 under the factual climate could be noticed for five southern basins, Kafirnigan, Zeravshan, Vakhsh, Tupalang and Murgab, and only for the first one, this trend disappears under the counterfactual climate. For three catchments, Sarysu, Bukhtarma and Isfara, no significant trends were found under both climate. According to the visual comparison of trend lines (Fig. 6, S2), there are four catchments from 12 with essential differences in trends under two climates: Derkul, Shagan, Vakhsh and Murghab. The same as for mean discharge, both trends for the Murghab are negative, but the levels of trend lines differ, with the higher level under the factual climate. It is the opposite for the Vakhsh: though both trends are also negative, the slope under the factual climate is stronger, suggesting a decrease in high flows due to changing climate. The trends in extreme precipitation (95th percentile) in most cases correspond to the high river discharge trends (Q5) by increasing tendency in the northern and decreasing in most southern basins (Figs. 6, Fig. S2 and S4).

In addition, a comparison of slopes disregarding the significance of trends allows us to conclude that slopes are higher under the factual climate for all three variables in Derkul, Shagan, Tobol, Zhabay and Murghab, and for two variables in Bukhtarma and Isfara, which means that water availability is higher in these basins under human-induced climate change. On the opposite, slopes are lower under the factual climate for all three variables in Kafirnigan, Zeravshan and Vakhsh, which means that water availability is becoming lower in these catchments under changing climate.

This allows us to conclude that if statistically significant positive trends for all three (or two, in the case of Tobol) variables found under the factual climate for Derkul, Shagan and Tobol disappeared under the counterfactual climate, then it is highly likely that these trends could be attributed to climate change (Fig. 6). These trends correspond well to trends in precipitation under both climates (Fig. 6, Fig. S3). The same logic leads to the conclusion that the average levels of river discharge, low flow and high flow in Murghab have increased during the historical study period due to climate change, though the decreasing trends during this period were maintained (Fig. 6). Also, the negative statistically significant trends in mean discharge under the factual climate in Sarysu and Kafirnigan, which are not found under the counterfactual climate, could be attributed to climate warming (Fig. S2). Besides, the increasing trend in Q95 with the higher slope for Bukhtarma under the factual climate most probably means that low flow in this catchment has increased due to changing climate (Fig. S2–S4). And the

visible difference in trend lines for Q5 in Vakhsh suggests decreasing probability of high flows in this basin under climate warming (Fig. S2).

Figure 7 presents the changes in long-term mean monthly river discharge for the period from 1955 to 2014 driven by the factual and counterfactual climate datasets. Changes in river discharge are driven mainly by two factors: increasing air temperature in the factual datasets across all catchments and changes in precipitation.

In all river catchments under study, river discharge increases at least in one of the spring months, and in six catchments in all three spring months under factual climate. This is caused by the increasing amount of precipitation for majority catchments (Figure S4B) in this period (e.g., an increase in April in 9 catchments) that leads to higher river discharge or higher temperature that provokes earlier snowmelt and shifting of spring flood to an earlier period. Temperature changes affect not only the spring flood timing and magnitude but also the snow accumulation during the cold period.

Similar to the annual trends, the mean monthly discharge has increased in all seasons driven by the factual data compared to the counterfactual data in two northern catchments, Derkul and Shagan, and in the Murghab catchment in the south of the research domain. The other three catchments located in Kazakhstan (except Sarysu) have higher discharge from October to April driven by the factual climate data. In the Sarysu catchment, discharge is lower in all months except March under the factual climate. Three catchments in the central

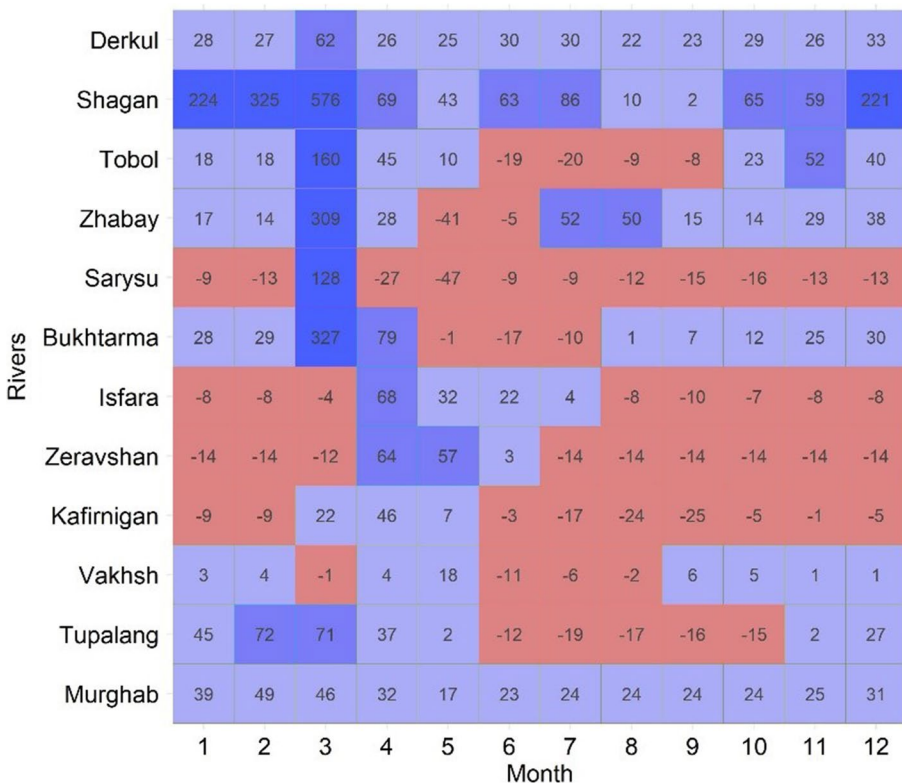


Fig. 7 Changes (%) in the long-term mean monthly river discharge between simulations driven by the factual and counterfactual climates over 12 river catchments for the period from 1955 to 2014

part, Isfara, Zeravshan, and Kafirnigan, have higher discharge only during 3–4 months in spring–summer under the factual climate, and lower streamflow in the rest 8–9 months. The Vakhsh and Tupalang have lower discharge in 3–5 months in summer–autumn driven by the factual climate, and increases in the rest seasons, which are minor for Vakhsh but more notable for Tupalang.

The monthly results in Fig. 7 are in accordance with the annual results (Fig. 5 and Fig. 6), and better illustrate seasonal changes occurring in the study region.

5 Discussion

The analysis of climate datasets in the historical period 1955–2014 showed statistically significant rising trends in temperature for GSWP3-W5E5 and three ESM datasets (“historical” runs) across all 12 study catchments. Higher temperature leads to higher evapotranspiration and melting of snow and glaciers. In terms of snow, the rising temperature provokes earlier snowmelt periods and earlier spring flood peaks in many rivers under study. Similar results but under different projection scenarios were found by numerous studies (Hagg et al. 2013; Didovets et al. 2021; Kalashnikova et al. 2023; Schaffhauser et al. 2023). At the same time, it leads to smaller snowmelt accumulation in terms of time and amount. It can be also observed in decreasing signals for river discharge in winter and summer months, especially in mountains. As expected, in the counterfactual climate time series from both datasets, these trends are missing.

However, there are no homogenous trends in precipitation in datasets based on GSWP3-W5E5 and ESMs, neither in the factual time series nor in the counterfactual ones. Despite rising temperatures in the factual climate data, positive trends in factual precipitation in three catchments in the northern part (Shagan, Derkul, Tobol) caused also positive trends in river discharge. Similar dependencies are found also for the low and high flow indices. Our results confirm that climate change could lead to an increase in the frequency of hydrological extremes like floods, especially in the northern part of Kazakhstan. The estimated trends in climate variables and streamflow as well as simulated effects of climate change on river discharge in Central Asia, including those presented in this paper, are subject to uncertainties that arise from various factors. They include the low density of meteorological stations in general and lack of meteorological observations in some areas, and the uncertainty of reanalysis of climate data resulting from that, as well as not a sufficiently dense network of hydrological gauges, and often too short time series of measured discharge. These factors may lead to inaccuracies in simulated river discharge and trends in climate variables and streamflow over the historical period, and can potentially influence the conclusions based on them.

For example, the negative streamflow trends in Vakhsh and Zeravshan under both factual and counterfactual climates correspond to very similar precipitation time series with negative trends under both climates (see Fig. S2–S4). This could be related to inaccuracies of GSWP3-W5E5 data or the approach applied by Mengel et al. (2021) for producing counterfactual climate in this region. Another example is Murghab, where precipitation has a small positive trend under factual climate changing to a small negative trend under counterfactual climate, both leading to statistically significant negative trends in discharge under both climates (stronger under counterfactual). At the same time, the 95th percentiles of precipitation show negative trends under both climates. The negative trend in streamflow under factual climate despite of slightly increasing annual precipitation could

be explained by increasing temperature resulting in higher evapotranspiration in this catchment. The negative trends in discharge under both climates may have the same reasons as listed above.

The results based on ESMs scenario data confirm the general pattern of attribution of climate change to trends in discharge based GSWP3-W5E5 across 12 catchments (Fig. 6 and Figures S5–S7 in Supplementary material).

However, the results based on three ESMs have shown a large bias in annual precipitation for several mountainous catchments (e.g., Vakhsh and Zeravshan) in our study area, leading to unrealistic very strong downward trends in discharge. It could be caused by different factors like the low density of observations in the mountainous region of Central Asia, and too low a resolution of ESMs for such areas. Therefore, in our case, we decided to use simulations based on ESMs only as additional information and placed them in SM.

In this paper, we focused on detection of trends in river discharge (annual mean, Q5 and Q95) and their attribution to climate change, but sensitivity of extreme precipitation and extreme streamflow with increased temperature (see, e.g., Yin et al., 2018; Ghausi & Ghosh, 2020; Shen & Chui, 2021) was not analyzed in our study. For example, in the paper by Yin et al. (2018), it was shown that storm runoff extremes increase at rates higher than proposed by Clausius-Clapeyron scaling ($6\text{--}7\%/^{\circ}\text{C}$) in most regions of the globe, and they are close to or exceed those of precipitation extremes increase, though spatial variability is large. A similar conclusion was made in the paper by Ghausi and Ghosh (2020) for a large region in South and Central Asia. However, an opposite was found by Shen and Chui (2021) for three watersheds in the USA: despite floods were highly related with precipitation extremes, the scaling of flood temperature was always lower than that of extreme precipitation temperature.

6 Conclusions

The rise in mean annual air temperature in the Central Asian region is higher than the global mean. In recent decades, Central Asian countries have experienced devastating droughts, resulting in water scarcity for both irrigation and hydropower. These events led to higher food prices and put additional stress on electricity production. At the same time, water disputes between citizens of different countries sparked border conflicts over the last decades. Such kind of water-related tensions could result from natural climate variability or from consequences of anthropogenic climate change impact. In this study, we investigated possible climate change impacts on water resources in the region which have occurred by now. The main goal of this paper was to detect trends in streamflow of 12 river catchments across Central Asia during the last six decades by applying the hydrological model SWIM driven by the factual and counterfactual (detrended) climate datasets, and in case of statistically significant differences between these trends to attribute them to climate change.

The results show that the annual and seasonal streamflow trends of three rivers in the northern part of Kazakhstan, Derkul, Shagan, and Tobol, can be attributed to climate change. A similar tendency was observed for the low and high flows in these three catchments, and their increasing trends could be also attributed to changing climate. At the same time, our study showed decreasing trends under factual climate in Sarysu and Kafirnigan catchments, and they also could be attributed to climate change.

Besides, the increasing trend in low flow for Bukhtarma under the factual climate most probably is due to slightly increasing precipitation. And the visible difference in trend lines for high flow in Vakhsh suggests decreasing probability of high flows in this basin under

climate warming. Also, our analysis suggests that the average level of river discharge in Murghab has increased during the historical study period due to climate change, though the decreasing trend during this period was maintained. This result is sound despite of possible influence of changing land use (irrigated agriculture) in this case, which was not implemented in the modelling, as this could only reduce river discharge.

There is no clear evidence of climate change effects on changes in annual flow for other catchments: Zhabay (similar increasing trends under both factual and counterfactual climates), as well as Zeravshan and Vakhsh (similar decreasing trends under both climates). And there are practically no trends found for annual mean flow under both climates for Isfara, Bukhtarma, and Tupalang. Nevertheless, considering changes in the seasonal flows, there is a clear signal of shifting spring peaks to earlier time due to higher temperatures and earlier snowmelt.

The signals of climate change attribution to river discharge trends found in this study show that both the annual and seasonal dynamics as well as extremes are affected in different regions of Central Asia. These signals highlight the urgency of climate actions and the need for improved observational data and climate impact assessments to be conducted to develop effective adaptation strategies for the future. Additionally, Central Asian countries need to cooperate in addressing the challenges posed by climate change.

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Data availability Climate-related data analyzed in this study are publicly available from www.isimip.org. The observational are not available to the public. Interested parties may obtain access to other data by contacting the corresponding authors and making a reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Authors give their consent for the publication.

Competing interests The authors declare no competing interests.

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Authors and Affiliations

Iulii Didovets¹  · Valentina Krysanova¹ · Aliya Nurbatsina² · Bijan Fallah¹ · Viktoriya Krylova³ · Assel Saparova² · Jafar Niyazov⁴ · Olga Kalashnikova⁵ · Fred Fokko Hattermann¹

✉ Iulii Didovets
didovets@pik-potsdam.de

¹ Potsdam Institute for Climate Impact Research (PIK), Climate Resilience, Potsdam, Germany

² Institute of Geography and Water Security Science, Laboratory of Water Resources, Almaty, Republic of Kazakhstan

³ Kazakh-German University, Center for Natural Resources and Sustainability, Almaty, Republic of Kazakhstan

⁴ Institute of Water Problems, Hydropower and Ecology, Academy of Sciences, Climatology and Glaciology Lab., Dushanbe, Republic of Tajikistan

⁵ Central-Asian Institute for Applied Geosciences, Department 2, Bishkek, Kyrgyz Republic