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SENSITIVITY ANALYSIS OF THE IMPACT OF CLIMATE CHANGE ON THE SYRDARYA RIVER RUNOFF

River runoff depends directly on climate conditions (e.g., temperature, precipitation and evapotranspiration), which affect water balance at the watersheds scale. The present work was conducted to investigate the impact of climate change on runoff in the Syrdarya River Basin, Central Asia. To assess the impact of climatic variation on runoff, the temporal trends of runoff were explored using the sensitivities of runoff to precipitation, temperature and potential evapotranspiration, and the aridity index was evaluated with the modified method of climate elasticity. The results showed that the average coefficients of sensitivity of runoff to precipitation and potential evapotranspiration were 2.4 and -1.4, and the sensitivity to temperature was -0.8 respectively, indicating that a 10% increase in precipitation or potential evapotranspiration would lead to a 24% increase or a 14% decrease in runoff, respectively. Additionally, the average coefficient of sensitivity of runoff to the aridity index varied from 0.65 to 2.8. The average coefficients of the sensitivity of runoff to climatic variation appeared to have an inverse relationship with the runoff coefficient, showing that the lower the river flow of the basin became, the more sensitive the runoff would be with respect to climatic variation. The results confirm the high sensitivity of river runoff in the Syrdarya River Basin to climatic changes. Precipitation was identified as the dominant factor controlling runoff formation, whereas an increase in potential evapotranspiration contributes to a reduction in basin water availability. The obtained estimates can be used to project future changes in regional water resources under changing climatic conditions.

Keywords: river basin, climatic variation, sensitivity analysis, partial correlation, river runoff.

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Сырдария өзені ағынының климаттың өзгеруіне сезімталдығын талдау

Өзен ағыны тікелей климаттық жағдайларға (мысалы, температура, жауын-шашын және булану) байланысты, олар суайрық шкаласында су балансына әсер етеді. Бұл жұмыс Орталық Азиядағы Сырдария өзені бассейніндегі ағынға климаттың өзгеруінің әсерін зерттеу үшін жүргізілді. Климаттық өзгерістердің ағынға әсерін бағалау үшін ағынның уақытша үрдістері ағынның жауын-шашынға, температураға және ықтимал булану транспирациясына сезімталдығын пайдаланып зерттелді, ал құрғақшылық индексі климаттық серпімділіктің өзгертілген әдісімен бағаланды. Нәтижелер ағынның жауын-шашынға және ықтимал булану транспирациясына сезімталдығының орташа коэффициенттері 2,4 және -1,4, ал температураға сезімталдығы сәйкесінше -0,8 екенін көрсетті, бұл жауын-шашынның немесе ықтимал булану транспирациясының 10%-ға артуы ағынның сәйкесінше 24%-ға артуына немесе 14%-ға төмендеуіне әкелетінін көрсетеді. Сонымен қатар ағынның құрғақшылық индексіне сезімталдығының орташа коэффициенті 0,65-тен 2,8-ге дейін өзгерді. Ағынның климаттық өзгерістерге сезімталдығының орташа коэффициенттері ағын коэффициентімен кері пропорционалды болып көрінді, бұл бассейннің өзен ағыны неғұрлым төмен болса, ағынның климаттық өзгерістерге соғұрлым сезімтал болатынын көрсетеді. Алынған нәтижелер Сырдария өзені алабының су ресурстарының климаттық факторлардың өзгеруіне жоғары сезімтал екенін көрсетті. Өзен ағынының қалыптасуына атмосфералық жауын-шашынның шешуші әсер ететіні, ал потенциалды буланудың артуы алаптың сулылығын төмендететіні анықталды. Зерттеу нәтижелері су ресурстарының болашақтағы өзгерістерін болжау және өңірдегі климаттың өзгеруіне бейімделу стратегияларын жетілдіру мақсатында пайдаланылуы мүмкін.

Түйін сөздер: өзен алабы, климаттың өзгеруі, сезімталдықты талдау, ішінара корреляция, өзен ағыны.

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Анализ чувствительности речного стока Сырдарьи к изменению климата

Речной сток напрямую зависит от климатических условий (например, температуры, осадков и испарения), которые влияют на водный баланс в масштабе водосборных бассейнов. Настоящая работа была проведена для исследования влияния изменения климата на сток в бассейне реки Сырдарья, Центральная Азия. Для оценки влияния климатических изменений на сток были изучены временные тенденции стока с использованием чувствительности стока к осадкам, температуре и потенциальному испарению, а индекс засушливости был оценен с помощью модифицированного метода климатической эластичности. Результаты показали, что средние коэффициенты чувствительности стока к осадкам и потенциальному испарению составили 2,4 и -1,4, а чувствительность к температуре -0,8 соответственно, что указывает на то, что увеличение осадков или потенциального испарения на 10% приведет к увеличению стока на 24% или уменьшению на 14% соответственно. Кроме того, средний коэффициент чувствительности стока к индексу засушливости варьировался от 0,65 до 2,8. Средние коэффициенты чувствительности стока к климатическим изменениям, по-видимому, имели обратную зависимость от коэффициента стока, показывая, что чем ниже становится речной сток в бассейне, тем чувствительнее сток к климатическим изменениям. Полученные результаты подтверждают высокую чувствительность речного стока бассейна Сырдарьи к климатическим изменениям. Установлено, что атмосферные осадки оказывают наибольшее влияние на формирование стока, тогда как увеличение потенциального испарения способствует снижению водности бассейна. Полученные оценки могут быть использованы для прогнозирования изменений водных ресурсов региона.

Ключевые слова: речной бассейн, климатические изменения, анализ чувствительности, частичная корреляция, речной сток.

Introduction

River runoff is a key indicator of renewable water resources and plays a critical role in both human and natural systems. Any significant change in runoff has significant social, ecological and environmental consequences. Climate change significantly impacts river runoff, with sensitivity varying across regions and seasons. Studies have shown that runoff is generally more sensitive to changes in precipitation than temperature (Yao et al., 2012). The runoff elasticity (ratio of runoff change to precipitation change) typically ranges from one to three, while runoff temperature sensitivity indicates decreases of 2-6% per degree Celsius warming in many basins (Tang & Lettenmaier, 2012). Arid and semi-arid regions often exhibit higher sensitivity to climate changes (Tang & Lettenmaier, 2012; Chen et al., 2024). The significant reduction of glacier areas in Central Asia, where glaciers are the main source of river feeding, serve as an indicator of this (Nurakynov et al., 2023). Seasonal variations in sensitivity are also observed, with transitional and fall seasons showing greater sensitivity than wet seasons (Chen et al., 2024). The climate change water impact index (ICCWI) has been developed to detect temporal and spatial sensitivity of basin runoff. Additionally, the aridity index has been used to assess streamflow sensitivity, with a 10% increase in aridity potentially leading to a 25.3% decrease in streamflow (Wang et al., 2017).

Climatic elasticity methods have been widely used to assess climate change impact on river runoff (Andréassian et al., 2016; Sharifi et al., 2024; Kumar et al., 2016). The elasticity approach is comparable to more complex hydrological modeling methods for assessing climate variation effect on the long-time runoff changes (Mo et al., 2025). In the last three decennaries, the climatic elasticity approach has undergone some expansions. Authors of the work (Schaake et al., 1990) first probed the climate elasticity of precipitation to basin runoff. In another work researchers (Fu et al., 2007; Liu et al., 2023) further combined precipitation and temperature together to evaluate runoff change. Using the analytical derivation based on the Budyko frame, authors (Yang & Yang, 2011) concluded the multiple climate elasticities to five climates indicators, i.e., precipitation, temperature, relative humidity, net radiation, and wind speed. Many studies, recently, have used multiple climatic elasticities to estimate the effect of climate on runoff in the historical period (Huang et al., 2016; Mandal et al., 2023). It is also a helpful approach for separating and quantifying the relative contributions of human activities and climate variation on runoff changes (Huang et al., 2024; Huang et al., 2025).

A major advantage of the sensitivity or elasticity method is the parsimony of data requirement. For example, to estimate εx, one requires only observations on the R-P-T relationship. Furthermore, the method can be implemented even with limited or no modeling experience. Finally, the results are in a form that is easily understood by stakeholders with different levels of scientific knowledge, making it a useful communication tool. Though this approach has its drawbacks. Even so, the approach has been shown to produce results that are of an order of accuracy comparable to many models and sufficient for most practical applications (Yang & Yang, 2011; Anderson et al., 2024; Seo et al., 2025). Reis et al. (2013) showed that climate elasticity estimates of river flow changes in the upstream Jaguaribe catchment closely matched those obtained from traditional statistical downscaling combined with hydrological modeling (Reis et al., 2013).

The current study primarily aims to identify the sensitivity of runoff to climate change in the Syrdarya River Basin. Understanding projections of future flow changes for the one of two largest river basins in Central Asia is critical to assessing the impacts of climate change on water resources.

The main objective of this study is to assess the sensitivity of streamflow to climate change in the Syrdarya River Basin. Understanding potential changes in streamflow is essential for evaluating climate change impacts on water resources in one of the largest transboundary river basins of Central Asia. The basin plays a critical role in supporting agricultural production, hydropower generation, and domestic water supply across Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan.

Recent decades have been characterized by rising air temperatures, shifts in precipitation patterns, and accelerated glacier retreat in the Tien Shan Mountains (Yao et al., 2012; Nurakynov et al., 2023). These changes directly affect runoff formation and may alter regional water availability. Given the high degree of water resource utilization and increasing climate-related pressures, assessing streamflow sensitivity to precipitation, temperature, and potential evapotranspiration is essential for improving water resource management and developing climate adaptation strategies in the region.

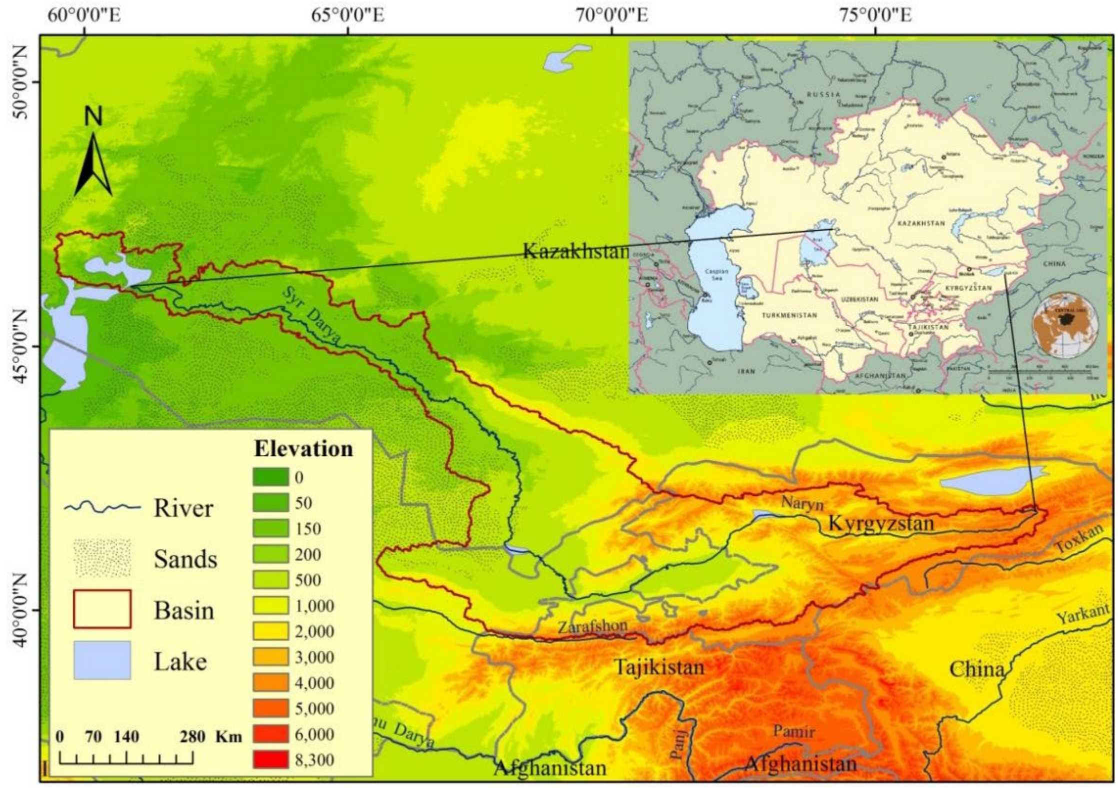
Study area

The Syrdarya River Basin (Figure 1) is one of the most important transboundary river basins in Central Asia, was selected as the study site for sensitivity analysis of runoff to climate and land-use changes. This basin stretches from 39°23'- 46° northern latitude and 61°-78°24' east longitudes and extends across an area of 219,000 km2.

The river runoff is formed by melting glaciers and snow and therefore varies greatly both seasonally and from year to year. Extremes include dry years – they are characterized by droughts – and high-water years – they are characterized by floods; both phenomena are potentially dangerous for the basin economy. The functioning of reservoirs on the Naryn River (the main tributary located in Kyrgyzstan and Uzbekistan), especially the Toktogul reservoir in Kyrgyzstan, is critical for the provision of water to agricultural areas downstream (Fergana Valley and further downstream to Uzbekistan and Kazakhstan), as well as for upstream electricity production, mainly in Kyrgyzstan. About 90% of the average annual river flow is regulated by reservoirs. Most of the reservoirs are used mainly for irrigation and flood prevention (Pradhan et al., 2022; Shannon et al., 2023).

The river serves as a major source of water for agriculture, industry, domestic supply, and ecosystem functioning, and discharges huge amounts of precipitation and freshwater into the Northern Aral Sea, thereby regulating seawater levels and biogeochemical cycles (Pradhan et al., 2022; Wegerich et al., 2015).

Figure 1
Map of study area



Note: Compiled by the authors.

The land cover is dominated by arid and alpine vegetation – grasses and shrubs, which occupy about 78% of the basin area. Forests, covering about 8% of the area, are located on frontal alpine ridges exposed to the main winds and receiving more precipitation. About 7% are swamps, and up to 5% are bare land, cliffs, and other low-fertility areas. The remaining area is covered by bodies of water and perennial snow and glaciers.

Agricultural land use in the Syrdarya River Basin The area of pastures is 280,000 km² (55% of the total basin area) and contains cattle, sheep, goats, pigs, horses and camels. The area of arable land is 35,000 km² (representing 8% of the basin area) and approximately 80% of this land is irrigated. It is important to note that orchards, vineyards and other types of cultivated land are excluded from this estimate. Much of the arable land is located in the Fergana Valley (including Jalal-Abad, Osh, Batken, Andijan, Namangan, Fergana, and Sughd provinces), which makes up about one-tenth of the basin and is home to about 55% of the population. The main agricultural products in this region include wheat, potatoes and cotton (Savoskul et al., 2003; Pradhan et al., 2022).

Materials and methods

Data

Data from 19 meteorological stations located within the basin and the surrounding areas were selected. Also, average annual data on air temperature (T), precipitation (P) and potential evapotranspiration (PET) from 1930 to 2015 was collected with Climatic Research Union high resolution gridded datasets – CRU TS4.00 and Database for open use of observation results at meteorological stations of the RSE "Kazhydromet". Given the limited availability and lack of observations data over the Syrdarya Basin, this study used freely available datasets. The Climatic Research Union dataset (CRU) is chosen for several reasons. Firstly, the dataset is based on a large number of stations. The data covers all land areas of the Earth. It includes mean daily temperature (TMP), diurnal temperature range (DTR), maximum and minimum air temperature (TMX and TMN), precipitation (P), vapor pressure (VAP), cloud cover (CLD), rain day counts (WET), ground frost frequency (FRS) and potential evapotranspiration (PET). The CRU dataset has 0.5° by 0.5° data resolution, based on meteorological measures (Harris et al. 2020).

Prior to analysis, all climatic variables were subjected to quality control procedures. Missing observations from meteorological stations were checked against neighboring stations and available gridded data where possible. Annual values of precipitation, air temperature, and potential evapotranspiration were calculated from monthly records to ensure temporal consistency with the climate elasticity framework, which is based on long-term annual averages.

To obtain basin-scale climatic characteristics, CRU TS grid cells located within the Syrdarya Basin were spatially averaged. The use of annual values reduces the influence of short-term variability and is consistent with the assumptions of long-term water balance analysis employed by the climate elasticity method.

Climatic elasticity method

We estimated the effect of climate variation on runoff using the climatic elasticity method of river runoff proposed by Schaake (Schaake et al. 2020). The sensitivity coefficient (ε_x) is determined by the proportional change in runoff (R) separated by the proportional change in a climate variable (X), such as potential evapotranspiration, temperature or precipitation (Hu et al. 2012), and is expressed as follows:

$$\varepsilon_x = \frac{\partial R/R}{\partial X/X} \quad (1)$$

namely:

$$\frac{\partial R}{\partial X} = \varepsilon_x \frac{R}{X} \quad (2)$$

In many previous studies, climate elasticity was estimated based on mean annual climatic variables (Dooge et al. 1999; Zheng et al. 2009; Arora et al. 2002). According to work (Arora et al. 2002), the change in basin runoff (R) may be explained as a function of the change in precipitation (P) minus potential evapotranspiration (PET):

$$\frac{\partial R}{R} = \frac{\partial P}{P}(1+\beta) - \beta \quad (3)$$

where the factor $\beta$is the sensitivity index, the value of which is proportional to the aridity index (Arora et al. 2002):

$$\beta = \frac{\varphi f'(\varphi)}{1 - f(\varphi)} \quad (4)$$

where $f(\varphi)$ is the function of φ (orx) and the detailed expressions of $f(\varphi)$ are given in (Yang & Yang, 2011). The coefficient β may be considered as a sensitivity index in a broad sense. If only one of precipitation or potential evaporation changes, then a upwards value of β means a larger change in runoff.

From Eq. (4), the surface runoff elasticity to precipitation, may be explained as follows:

$$\varepsilon_p = \frac{[\partial R/R]}{[\partial P/P]} = 1 + \beta \quad (5)$$

$$\varepsilon_{Eo} = \frac{[\partial R/R]}{[\partial PET/PET]} = -\beta \quad (6)$$

And, the surface runoff elasticity to temperature can be calculated according to research (Grijsen et al. 2013) as:

$$\varepsilon_T = \frac{[\partial R/R]}{[\partial T/T]} = \varepsilon_p * \frac{[\partial PET]}{[\partial T]} \quad (7)$$

The obtained sensitivity coefficients were used to assess the response of streamflow to changes in climatic factors. Higher absolute values of the coefficients indicate a stronger influence of the corresponding climatic variable on streamflow generation.

Methodological Uncertainties and Limitations

Although the climate elasticity method offers a parsimonious alternative to complex hydrological models, it has several inherent limitations. First, the climate elasticity approach assumes long-term equilibrium conditions and does not explicitly represent processes such as snow and glacier melt, groundwater interactions, or reservoir regulation. Thus, the coefficients reflect integrated basin-scale responses rather than detailed hydrological mechanisms. Second, climatic inputs were derived from the CRU TS dataset with a spatial resolution of 0.5°. Although this dataset is widely used and provides one of the longest and most consistent climate records available for Central Asia, uncertainties remain in mountainous regions where meteorological observations are sparse and climatic gradients are strong. However, it remains one of the most consistent long-term climate datasets available for Central Asia (Guo et al., 2018). Third, reservoir regulation and irrigation withdrawals may influence the climate–runoff relationships estimated by the elasticity approach. Despite these limitations, the approach remains robust for first-order assessments of long-term climatic impacts (Yang & Yang, 2011).

Although the climate elasticity approach provides a practical and parsimonious framework for evaluating long-term streamflow responses to climatic variability, several limitations should be acknowledged.

Compared with physically based hydrological models such as SWAT, VIC, HBV, or WEAP, the climate elasticity method requires substantially fewer input data and calibration parameters, making it particularly suitable for data-scarce regions. However, it should be regarded as a first-order assessment tool rather than a substitute for process-based hydrological modeling. Future studies may benefit from combining climate elasticity analysis with physically based modeling approaches to better quantify the impacts of glacier retreat, reservoir regulation, and future climate scenarios on water resources in the Syrdarya Basin.

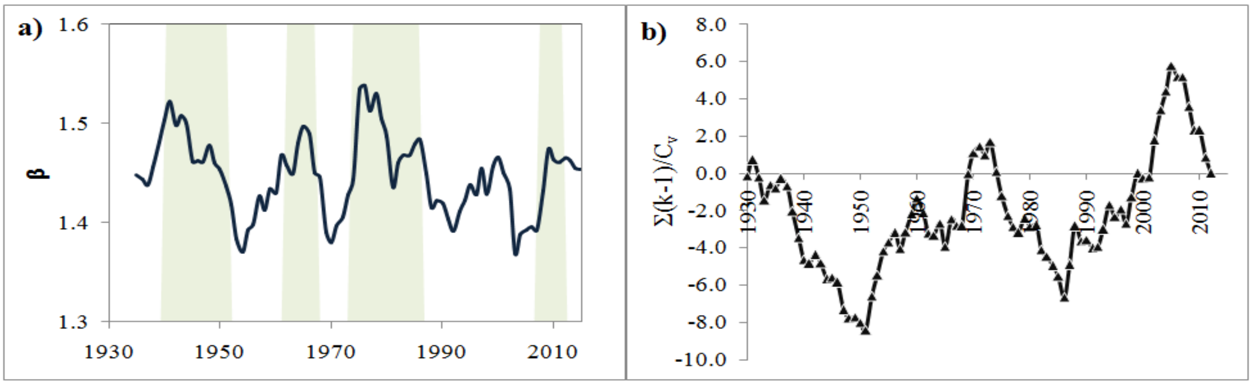
Results and discussion

Sensitivity index in the basin

The arid region is totally a water-limited area due to both limited water input (low precipitation) and high temperatures, which act to grow PET. On average, the Syrdarya Basin as a whole is water-limited, because more than half its area falls into arid zone with limited water yields.

The average value of the sensitivity coefficient varied from 0.65 to 2.8 in the Syrdarya River Basin. The arid areas are very sensitive $\beta > 1$ and show very low discharges ($\frac{R}{P} < 1$). It should be noted that the sensitivity coefficient changes over time; it is lower during high water phases and higher during low water periods (Figure 2).

Figure 2
Temporal variation of the basin sensitivity coefficient during 1930–2015 (a) and corresponding difference integral curve of annual runoff (b). Grey shaded areas indicate low-flow periods identified from runoff records



Note: Compiled by the authors.

As Figure 2a shows, the sensitivity index varies greatly from year to year. Moreover, the sensitivity index increases in the low-water period, which occurred in the basin in 1939-1951, 1962-1967, 1974-1987 and 2008-2012. Also, during the high-water flow phases decreases. The periods of high and low water flows indicated in Figure 2b, $\Sigma(k_i\text{-}1)/Cv$ – the current ordinates of the difference integral curve showed that there were cycles of different duration in the annual average runoff fluctuations. During the low water flow periods overall average of the sensitivity index was 1.49. Within the high-water periods, sensitivity index was about 1.39.

The Sensitivity of Runoff to P, PET and T

To assess the impact of climate variation on river runoff, most researchers have applied the concept of climate elasticity to investigate the runoff response to climate change (e.g., precipitation and potential evapotranspiration, temperature). The sensitivity of runoff to precipitation, PET and temperature is determined using Eqs. 5, 6 and 7, respectively. The precipitation, PET and temperature elasticity of the watershed in the Syrdarya River Basin are listed in Table 1. The values of ε_p for the basin were 1.65 to 3.76, with means of 2.4. The values of ε_{Eo} for the basin were -0.65 to -3.76 and ε_T for the basin were -0.45 to -1.66. The signs of ε_p, $\varepsilon_{Eo}$and ε_T indicate that the runoff is expected to have apositive trend with an increase in precipitation, but a negative trend with an increase in PET and temperature. The findings also show that a 10% growth in precipitation would result in a 24% growth in the runoff, while a 10% increase in PET and T℃ would induce a 13% and 8% decrease in runoff, respectively. As displayed in Table 1, the value of precipitation elasticity (ε_p) is much larger than other climate variable elasticities, shows that runoff is more sensitive to precipitation than to other climate variables (i.e., PET and temperature).

Table 1
Elasticity of precipitation, potential evapotranspiration and temperature to river runoff

Coefficient	Stations					
	Namagan	Keles	Tomenaryk	Naryn	Chinaz	Arys
ε_p	2.05	2.12	3.76	1.65	1.74	2.93
ε_{Eo}	-1.05	-1.12	-2.76	-0.65	-0.74	-1.93
ε_T	-0.63	-0.67	-1.66	-0.39	-0.45	-1.16

A correlation analysis was used to further investigate the relationships between precipitation, PET, T and runoff. As shown in Table 2, the positive correlation between precipitation and R (ρP,R) and the negative correlation between PET and R (ρPET,R) are statistically significant at the 0.05 level, which suggests that the runoff will increase or decrease with an increase or decrease in precipitation, but decrease or increase with an increase or decrease in PET.

Furthermore, a value of $\rho_{P,R}$ greater than $\rho_{PET,R}$ and $\rho_{T,R}$ for the Syrdarya River basin indicates that the impact of precipitation on runoff is more important than that of PET and temperature. The correlation coefficient between temperature and PET ($\rho_{T, PET}$) is statistically significant at the 0.01 level, indicating that the interactions between temperature and PET are stronger. Whereas, the relationship between precipitation and PET ($\rho_{P,PET}$) are good. Eliminating the effects of PET (precipitation) on runoff, the partial correlation coefficients $\rho_{P,R\text{-}PET\text{-}T}$ ($\rho_{PET,R\text{-}P\text{-}T}$ and $\rho_{T,R\text{-}P\text{-}PET}$) between precipitation and runoff (between PET, temperature and runoff) are also exposed in Table 2. As observed from the table, the differences between $\rho_{P,R}$ and $\rho_{P,R\text{-}T\text{-}PET}$are smaller, while the differences between $\rho_{PET,R}$ and $\rho_{PET,R\text{-}P\text{-}T}$ are greater. However, it can also be noted that the downstream of the river basin are less correlated with precipitation, while the relationship with PET is higher. This can be explained by the fact that in the lower part of the basin there are almost no tributaries.

Table 2
Coefficients of correlation and partial correlation among climate variables and river

Coefficients	Value		
	Upper	Middle	Lower
$\rho_{P,PET}$	-0.59	-0.41	-0.33
$\rho_{T,PET}$	0.47	0.52	0.57
$\rho_{T,P}$	-0.03	-0.07	-0.01
$\rho_{P,R}$	0.55	0.61	0.33
$\rho_{PET,R}$	-0.37	-0.39	-0.43
$\rho_{T,R}$	-0.01	-0.07	-0.13
$\rho_{P,R\text{-}T\text{-}PET}$	0.40	0.48	0.18
$\rho_{PET,R\text{-}P\text{-}T}$	-0.12	-0.25	-0.40
$\rho_{T,R\text{-}P\text{-}PET}$	-0.09	-0.12	-0.14

The correlation analysis results provide further insight into the relationships between climatic variables and streamflow. The strongest relationship was observed between precipitation and streamflow. Positive correlation coefficients confirm the dominant role of atmospheric moisture input in the formation of water resources within the basin. Since most of the Syrdarya Basin is located in arid and semi-arid environments, additional precipitation contributes directly to both surface and subsurface runoff generation.

Potential evapotranspiration exhibited a consistent negative relationship with streamflow. This pattern can be explained by increased water losses from soil surfaces, vegetation, and water bodies under higher evaporative demand, resulting in a reduced volume of water available for runoff generation. Similar findings have been reported for the Nile River Basin, the Luan River Basin, and several catchments in North America (Hasan et al., 2018; Wang and He, 2017; Sankarasubramanian et al., 2001).

The relatively weak relationship between air temperature and streamflow is primarily associated with the indirect influence of temperature on hydrological processes. In most cases, temperature affects runoff through its impact on potential evapotranspiration and the overall basin water balance. Consequently, the correlation between temperature and streamflow is considerably weaker than that between precipitation and streamflow.

Spatial variability was also evident within the basin. In the upper reaches, streamflow formation is largely controlled by snow and glacier melt as well as precipitation inputs. In the lower reaches, the influence of evapotranspiration and water management practices becomes more pronounced, leading to a weaker precipitation–streamflow relationship and a greater contribution of potential evapotranspiration. Similar spatial patterns have been documented in many large transboundary river basins located in arid regions.

The estimation of elasticity

Climate elasticity, are widely used for the quantitative evaluation of the effects of climate change on river runoff in different regions of the world. The physically based hydrological models are able to represent the complex spatial-temporal variations in evapotranspiration, soil moisture, and runoff (Sankarasubramanian et al., 2001), and this method is by far the most common. However, this approach has uncertainties in the structure and the parameters of the models and may sometimes lead to a significant bias in reflecting the response of runoff to climate change if the model is not well validated (Ten et al. 2025). An alternative method based on climate elasticity of river runoff has been tested and found to be relatively more effective and simpler than hydrological modeling in a number of studies, and this method yields the overall change in runoff in a basin with fewer data and parameters (Wijekoon et al., 2022; Hu et al., 2012).

Changes in precipitation, temperature and PET can influence the annual streamflow. In catchment, from a water balance perspective, the annual runoff depends on the difference between the annual amount of precipitation and evapotranspiration. In the present study, the ratio of the sensitivity coefficient of runoff to P (2.4) is larger than the ratio of runoff to PET (-1.4) and T (-0.8), which indicates that the basin is more sensitive to precipitation, which has a greater capacity to impact the runoff. As shown in Table 2, the partial correlation results indicate that the effects of precipitation on runoff are independently related to the lesser effects of PET, while the effects of PET on runoff depend on the greater precipitation effects.

To date, relatively few studies have applied the climate elasticity approach to the Syrdarya River Basin and other major river systems in Central Asia. Nevertheless, the obtained estimates were compared with results reported for other arid and semi-arid river basins. All of the results of this study are similar to those of other studies (Hasan et al., 2018; Andréassian et al., 2025) the effects of the available water (precipitation) on river runoff are greater, while the potential evapotranspiration (which reflects the energy conditions) has a smaller effect. This is in good agreement with the findings by the authors of the work (Sankarasubramanian et al., 2001)., which indicated that a larger P elasticity occurs in more arid regions.

Similar patterns of high precipitation elasticity have been observed in other arid and semi-arid regions worldwide. Studies in Australia have reported ε_p values ranging from 2.0 to >3.0 in water-limited catchments (Chiew 2006). In the Nile Basin, precipitation elasticity typically exceeds 2.0 in arid sub-basins, whereas humid headwaters show $\varepsilon_p < 1$

(Hasan et al., 2018). At the global scale, basins with an aridity index > 1 (water-limited) generally have ε_p exceeding approximately 2 (Tang et al., 2020).

The obtained results are consistent with findings reported for other water-limited river basins worldwide. For example, a study of five river basins in south-eastern Brazil demonstrated that streamflow is highly sensitive to changes in precipitation and potential evapotranspiration, with streamflow responses increasing under long-term climatic shifts (Deusdará-Leal et al., 2022). The authors reported that a 1% decrease in precipitation resulted in a 1.21–2.19% reduction in streamflow, while increasing potential evapotranspiration contributed to additional runoff declines. Similar to the Syrdarya Basin, precipitation was identified as the dominant driver of streamflow variability, and the sensitivity of runoff increased under drier climatic conditions. These similarities suggest that despite differences in climate and physiographic settings, water-limited basins exhibit comparable hydrological responses to climatic variability.

The results indicate a strong dependence of water resources in the Syrdarya River Basin on climatic factors. Precipitation was identified as the dominant driver of streamflow formation. The mean precipitation sensitivity coefficient was 2.4, indicating a substantial streamflow response even to relatively small changes in atmospheric moisture input. This relationship is particularly important for water-scarce regions of Central Asia, where the Syrdarya serves as a critical source of water for irrigation, domestic supply, and energy production.

According to the obtained results, a 10% decrease in precipitation may result in an approximately 24% reduction in streamflow, whereas a 10% increase in potential evapotranspiration may reduce streamflow by about 14%. These findings highlight the vulnerability of the basin to increasing aridity and ongoing climatic changes. An additional source of uncertainty is the continued glacier retreat in the Tien Shan Mountains, which may further increase the dependence of streamflow on precipitation and interannual climate variability in the future.

The derived sensitivity coefficients can be used for preliminary assessments of potential changes in water availability under different climate scenarios and may support the development of adaptation strategies for regional water resource management.

The climate elasticity approach has been widely applied to assess the impacts of climate change on water resources due to its relatively modest data requirements and its ability to quantify streamflow responses to climatic variability (Schaake, 1990; Andréassian et al., 2016). Previous studies conducted in various river basins worldwide have shown that streamflow in arid and semi-arid regions is generally more sensitive to changes in precipitation than to changes in air temperature or potential evapotranspiration (Sankarasubramanian et al., 2001; Arora, 2002; Hasan et al., 2018).

The sensitivity coefficients obtained for the Syrdarya River Basin are consistent with patterns reported for other arid river basins. Similar to many comparable regions, precipitation represents the primary control on streamflow generation, whereas the influence of temperature is expressed mainly through its effect on potential evapotranspiration and basin water balance (Yang and Yang, 2011; Hu et al., 2012; Wang and He, 2017). The agreement between the present results and previously published studies supports the reliability of the estimates and demonstrates the applicability of the climate elasticity approach for evaluating the response of water resources in the Syrdarya Basin to climate change.

The results also have important implications for transboundary water resource management in Central Asia. The Syr Darya River is shared by Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan, and supports irrigation, hydropower production, and domestic water supply across the region. The high sensitivity of streamflow to precipitation indicates that even relatively small changes in climatic conditions may lead to substantial changes in water availability. Consequently, future reductions in precipitation or increases in evaporative demand could intensify existing competition among water users, particularly during low-flow periods.

The obtained sensitivity coefficients may serve as a useful tool for preliminary assessments of climate-related water risks and can support the development of adaptation strategies, including improved reservoir operation, enhancement of water-use efficiency in irrigated agriculture, and strengthening of regional cooperation on transboundary water allocation. Given the projected warming and continued glacier retreat in the Tien

Shan Mountains, proactive adaptation measures will be increasingly important for maintaining water security and sustainable socioeconomic development throughout the Syr Darya Basin.

Conclusions

The obtained results are generally consistent with findings reported by physically based hydrological modeling studies conducted in climatically similar river basins.

Changes in runoff are an important part of the hydrological cycle and are affected by many factors, and a complicated feedback to climate change exists. Because of the intimate linkage between hydrology and climate, this relationship can be used as an indicator of climate change. In this investigation, the concept of the climate elasticity of basin runoff has been applied to quantify the sensitivity of runoff to climate change. The conclusions may be compiled as follows:

1) Precipitation and PET are the most important meteorological variables influencing changes in river runoff. Runoff was positively correlated with precipitation but negatively correlated with PET and temperature, and the runoff-precipitation relationships were stronger than the runoff-PET and runoff-temperature relationships.

2) The average ε_p, ε_{Eo} and ε_T were 2.4, -1.4 and -0.8, respectively, which indicated that a 10% increase in precipitation or PET or temperature would lead to a 24% increase or a 14% and 8 % decrease in runoff, respectively.

3) The average value of the sensitivity coefficient varied from 0.65 to 2.8 in the Syrdarya River Basin. The arid regions are very sensitive $\beta > 1$ and show very low runoff ($\frac{R}{P} < 1$). It should be stated that the sensitivity coefficient changes over the period; it is lower during high water phases and higher during low water phases.

In general, although in many cases, more accurate estimates on the influences of climate variation to runoff for a particular region still need physically-based hydrological modeling, the results here show the robust of the simple tool of climatic elasticity, which allows for providing a helpful overview of the response of long-time runoff to climate variation in the study area.

The obtained results provide a basis for assessing potential changes in water availability in the Syrdarya River Basin and can support the development of regional climate adaptation policies and sustainable transboundary water resource management in Central Asia.

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Conflict of interest

There is no conflict of interest.

Author Contributions

Conceptualization, Isklaiyeva G. and Sydyk N.; Methodology, Isklaiyeva G. and Sydyk N.; Software, Amangelgi A.; Validation, Amangelgi A., Sagat M. and Eskaliyeva Sh.; Formal Analysis, Sagat M.; Investigation, Isklaiyeva G. and Sagat M.; Resources, Eskaliyeva Sh.; Data Curation, Amangelgi A. and Eskaliyeva Sh.; Writing – Original Draft Preparation, Isklaiyeva G. and Sydyk N.; Writing – Review & Editing, A.A., Sagat M. and Eskaliyeva Sh.; Visualization, Sagat M.; Supervision, Isklaiyeva G.; Project Administration, Sydyk N.; Funding Acquisition, Sydyk N.

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