Impact Analysis of Different Upstream Development Scenarios on Runoff Variation in the Aksu River (Postprint)

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Abstract

The Saryjaz River originates in Kyrgyzstan (hereinafter referred to as Kyrgyzstan), with its inflow accounting for approximately 44.3% of the Aksu River' s water volume, which holds significant practical importance for ensuring the sustainable economic and social development of the Aksu region. In recent years, Kyrgyzstan has planned water resources development on the Saryjaz River (the upper reaches of the Aksu River), which will affect the water resources of the downstream Aksu River basin within our country' s territory. Based on runoff data from the Aksu River basin, this study quantitatively analyzed the runoff variation characteristics of the Saryjaz River and the impacts of different development scenarios on downstream runoff of the Aksu River. The results indicate that: during 1958-2015, the annual runoff of the Saryjaz River exhibited a significant overall increasing trend; the intra-annual distribution of runoff varied considerably, being mainly concentrated in July and August; runoff in spring and winter showed significant increasing trends, while summer and autumn displayed slight increasing trends; from an interdecadal perspective, except for the dry period of 1958-1959 and the wet period of 1990-1999, the remaining periods were normal-flow periods. The construction of inter-basin water transfer projects in Kyrgyzstan will have a significant impact on the runoff of the Aksu River. From a seasonal scale analysis, the construction of inter-basin water transfer projects will cause a reduction in downstream runoff of the Aksu River, with summer showing the highest sensitivity; from an annual scale analysis, the construction of inter-basin water transfer projects will cause a reduction in downstream runoff of the Aksu River, and as the volume of water transfer increases, the downstream runoff of the Aksu River will continue to decrease. The research findings can provide certain reference for our government in addressing the issue of impacts from Kyrgyzstan' s inter-basin water transfer project construction on the runoff of the Aksu River.

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Full Text

Analysis of Impacts of Different Upstream Development Scenarios on Runoff Variation in the Aksu River

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Abstract

The Sary-Jaz River originates in Kyrgyzstan, and its inflow accounts for approximately 44.3% of the total water volume of the Aksu River, playing a crucial role in ensuring sustainable economic and social development in the Aksu region. In recent years, Kyrgyzstan has planned to develop water resources in the Sary-Jaz River Basin (upstream of the Aksu River), which will affect water resources in the downstream Aksu River Basin within Chinese territory. Based on runoff data from the Aksu River Basin, this study quantitatively analyzes the runoff variation characteristics of the Sary-Jaz River and the impacts of different development scenarios on downstream Aksu River runoff. The results show that from 1958 to 2015, the annual runoff of the Sary-Jaz River exhibited a significant increasing trend, with pronounced intra-annual variation concentrated mainly in July and August. Runoff increased significantly in spring and winter, while showing slight increases in summer and autumn. In terms of interdecadal variation, the period from 1958–1959 was a relatively dry period, 1990–1999 was a relatively wet period, and the remaining periods were normal. The construction of an interbasin water transfer project in Kyrgyzstan will significantly impact Aksu River runoff. Seasonal-scale analysis reveals that the project will cause runoff reduction in the lower Aksu River, with summer showing the highest sensitivity. Annual-scale analysis indicates that the project will also cause runoff reduction, and as water diversion increases, downstream runoff will continue to decline. These findings can provide a reference for the Chinese government in addressing the impacts of Kyrgyzstan' s interbasin water transfer project on Aksu River runoff.

Keywords: Runoff; Development Scenarios; Hydraulic Engineering; Multiple Linear Regression Model; Aksu River; Sary-Jaz River

1. Introduction

Water resources are a limiting factor for sustainable economic and social development in the arid regions of northwestern China. The Tarim River Basin, located in southern Xinjiang, is characterized by a dry climate with low precipitation and high evaporation, representing a typical arid desert region. As China' s largest high-quality cotton production base and an important energy base, the Tarim River Basin faces increasing water resource uncertainty due to climate warming. Ensuring water supply is essential for sustainable basin development. The Aksu River, situated in the northwestern Tarim Basin, originates in Kyrgyzstan and consists of two major tributaries: the Kumalak River (known as the Sary-Jaz River in Kyrgyzstan) and the Toshkan River (known as the Aksai River in Kyrgyzstan). As the only perennial tributary supplying water to the Tarim River, the Aksu River contributes approximately 70% of the Tarim River' s main stream flow, playing a vital role in the formation, development, and evolution of the Tarim River.

The Sary-Jaz River, which originates in Kyrgyzstan, contributes about 44.3% of the Aksu River' s water volume, making it critical for sustainable development in the Aksu region. In recent years, Kyrgyzstan has planned water resource development in the Sary-Jaz River (upstream of the Aksu River), which will affect water resources in the downstream Aksu River Basin within China. During the Soviet era, Kyrgyzstan planned to divert water from the Sary-Jaz River (upstream of the Aksu River) to the Issyk-Kul and Chu River basins to address water shortages, but this plan was not implemented due to natural conditions and technical limitations. However, recent Kyrgyz media reports indicate renewed interest in developing Sary-Jaz water resources. In 2006, the Kyrgyz president announced that China and Kyrgyzstan would sign a memorandum to build hydropower stations on the Sary-Jaz River. In July 2013, the Kyrgyz vice prime minister proposed development projects for the Sary-Jaz River Basin and adjacent areas. If Kyrgyzstan develops the Sary-Jaz River, it will control the transboundary inflow to the Aksu River, reducing water volume entering the Tarim River and negatively impacting the Tarim River Basin. Therefore, studying the impacts of upstream water resource development in Kyrgyzstan on downstream runoff variation in the Aksu River holds significant scientific and practical importance.

While hydraulic engineering projects play major roles in flood control and water resource regulation, they also affect ecosystems, river morphology and hydrological regimes, and local climate. Numerous studies have examined glaciers, water cycling processes, and land use in the Aksu River Basin, but research on the impacts of upstream hydraulic projects on downstream runoff remains limited. This paper establishes development scenarios for Kyrgyzstan' s interbasin water transfer project based on Kyrgyz development plans and quantitatively analyzes the project' s potential impacts on downstream Aksu River runoff.

2. Study Area Overview

The Sary-Jaz River (78°05 -80°17 E, 41°22 -42°27 N) originates in the western Tianshan Mountains in Kyrgyzstan and is the largest tributary of the Aksu River. The river is approximately 242 km long with a total drop of 1,850 m and a drainage area of 12,887 km^2, of which 1,906.7 km^2 lies within China, accounting for about 14.8% of the total basin area. The basin topography is higher in the east and lower in the west, with an average elevation of approximately 3,200 m. The climate is cold with low temperatures, high humidity, and low evaporation.

The basin has permanent snow cover and extensive glaciers. According to the Chinese Glacier Inventory, there are 2,421 glaciers covering about 2,421 km^2, representing approximately 18.8% of the basin area.

Kyrgyzstan has abundant water resources but a relatively underdeveloped economy. According to a 2019 World Bank survey, the poverty rate in Kyrgyzstan reached 25.4%, with hydropower generation being a primary economic driver. Water resource assessments indicate that the Sary-Jaz River Basin has a hydropower potential of 147.2$\times 10^{8}$ kWh, but due to complex terrain, remote location, and harsh climate, these water resources remain largely undeveloped. In 2006, Kyrgyzstan's Vice Minister of Industry, Trade, and Tourism announced plans to establish cascade hydropower stations in the Sary-Jaz River Basin. Subsequently, in 2013, both the Kyrgyz president and vice prime minister expressed intentions to develop the Sary-Jaz River. According to Kyrgyz media reports, Kyrgyzstan plans to build 5 hydropower stations on the Sary-Jaz River. Once completed, Kyrgyzstan may implement an interbasin water transfer project to divert water from the Sary-Jaz River to the Issyk-Kul Basin for rational water allocation.

3. Data and Methods

3.1 Data Sources

This study collected digital elevation data, river networks, and hydrological station data for the Aksu River Basin. The Digital Elevation Model (DEM) was obtained from the SRTM data jointly measured by NASA and the National Geospatial-Intelligence Agency, with a resolution of 90 m (https://srtm.csi.cgiar.org). Basin boundaries and river network data were derived from HydroSHEDS data provided by the US Geological Survey (http://hydrosheds.cr.usgs.gov). Hydrological data consisted of monthly measured runoff data from the Xiehela and Shaliguilanke hydrological stations at the mountain outlets of the two tributaries, and the Xidaqiao hydrological station at their confluence (Table 2).

Due to the lack of runoff data for the Sary-Jaz River and because water resources in the basin remain largely undeveloped, this study used runoff data from the Xiehela hydrological station on the Kumalak River as a proxy for Sary-Jaz River runoff.

3.2 Methods

3.2.1 Mann-Kendall Trend Test The Mann-Kendall test is a non-parametric method for assessing long-term trends in data series, offering advantages such as minimal interference from outliers and wide applicability. Based on these advantages, this study employed the method to analyze runoff variation characteristics in the Sary-Jaz River from 1958 to 2015.

3.2.2 Multiple Linear Regression Model The composition of the Aksu River shows that inflow from the Sary-Jaz and Aksai rivers in Kyrgyzstan is strongly correlated with the main stream flow. This study established a multiple linear regression model between the two tributaries and the main stream to analyze how changes in Sary-Jaz River inflow affect downstream Aksu River runoff.

According to available information, Kyrgyzstan has no plans to develop the Aksai River, so its inflow is assumed to remain essentially unchanged. The multiple linear regression model was constructed based on runoff data from the Xiehela, Shaliguilanke, and Xidaqiao hydrological stations. The model is expressed as:

$$Y = b_0 + b_1X_1 + b_2X_2 +$$

where Y is the dependent variable representing runoff at the Xidaqiao station (10^8 m^3); X_1 and X_2 are independent variables representing runoff at the Shaliguilanke and Xiehela stations, respectively (10^8 m^3); b_0 is the constant term; b_1 and b_2 are regression coefficients for the respective stations; and is the error term.

4. Development Scenario Settings

During the Soviet era, Kyrgyzstan planned to divert water from the Sary-Jaz River to the Issyk-Kul and Chu River basins to address severe water shortages and achieve rational water allocation, but the plan was not implemented due to harsh natural conditions and technological limitations. If hydropower development in the basin succeeds, Kyrgyzstan will likely construct an interbasin water transfer project to divert water from the Sary-Jaz River Basin to the Issyk-Kul Basin (Figure 2). Additionally, water consumption for domestic use and economic activities such as mineral resource extraction associated with hydropower development will also consume substantial water resources.

The Soviet-era plan proposed a water diversion volume of 16$×10^{8}$ m^3, accounting for approximately 33.6% of the Sary-Jaz River' s multi-year average runoff (48.42$×10^{8}$ m^3). Considering China' s cooperation on transboundary rivers, a 30% reduction in inflow is set as the upper limit for the water transfer scenario. Therefore, based on the premise that water transfer from the Sary-Jaz River Basin to the Issyk-Kul Basin will reduce inflow, this study quantitatively analyzes the impacts of Kyrgyzstan's interbasin water transfer project on downstream Aksu River runoff variation at different time scales, assuming inflow reductions of 10%, 20%, and 30%.

In recent years, with economic development, population growth, and expansion of irrigated areas in southern Xinjiang, water demand has increased, intensifying water use conflicts between upstream and downstream areas. As a tributary of the Aksu River, the Sary-Jaz River provides about 44.3% of the Aksu River' s water volume. Although climate warming has increased runoff in the Sary-

Jaz River, agricultural irrigation in the Aksu River Basin has also consumed large amounts of water, increasing water resource pressure. Particularly during March-May, when spring irrigation demand is high in irrigated areas, if Kyrgyzstan diverts water from the Sary-Jaz River, it will exacerbate water supply-demand conflicts in the lower Aksu River Basin. Moreover, once a dry year occurs, these conflicts may further intensify, affecting not only socio-economic development in the basin but also potentially causing flow interruption in the Tarim River.

5. Results and Analysis

5.1 Runoff Variation Characteristics of the Sary-Jaz River

From 1958 to 2015, the annual runoff of the Sary-Jaz River showed a significant increasing trend ($P < 0.01$) at a rate of 0.0231$×10^{8}$ m^3 · a^{-1}, with an average annual runoff of 48.42$×10^{8}$ m^3. The highest and lowest annual runoff values occurred in 2005 and 1961, respectively. Intra-annual runoff distribution varied considerably, concentrated mainly in July and August, accounting for approximately 54.06% of annual flow. The lowest monthly runoff occurred in February, accounting for only 4.43% of annual flow. The difference between the highest and lowest monthly values reached 479.94 m^3 · s^{-1}.

Seasonal analysis revealed that from 1958 to 2015, average runoff in spring and winter showed significant increasing trends at rates of 0.014$×10^{8}$ m^3 · a^{-1} and 0.008$×10^{8}$ m^3 · a^{-1}, respectively, with winter having the lowest proportion of annual runoff. Summer and autumn average runoff showed non-significant increasing trends at rates of 0.114$×10^{8}$ m^3 · a^{-1} and 0.020$×10^{8}$ m^3 · a^{-1}, respectively, with summer having the highest proportion due to concentrated rainfall and high temperatures favorable for glacier and snowmelt (Table 3).

Interdecadal variation analysis showed that the period from 1958-1959 was a relatively dry period, 1990-1999 was a relatively wet period, and the remaining periods were normal (Table 4). The maximum average annual runoff was 52.46$×10^{8}$ m^3 during 1990-1999, while the minimum was 43.96$×10^{8}$ m^3 during 1958-1969, primarily due to higher precipitation in the 1990s.

5.2 Impact of Development Scenarios on Aksu River Runoff

5.2.1 Multiple Linear Regression Models at Different Time Scales Based on monthly runoff data from the Xiehela, Shaliguilanke, and Xidaqiao stations from 1958 to 2015, multiple linear regression equations were developed for different time scales (Table 5). F-tests verified the model fit, with all equations passing significance tests ($P < 0.05$), indicating good overall model performance. The results are consistent with Zhang Heng’ s research, demonstrating that the model simulates runoff well in the upper Aksu River Basin.

5.2.2 Sensitivity Analysis Using the scenario of Kyrgyzstan' s interbasin water transfer project causing a 10%, 20%, and 30% reduction in Sary-Jaz River inflow, and assuming runoff from the Toshkan River (Aksai River) remains unchanged, changes in downstream Aksu River runoff were calculated (Table 6).

Seasonal-scale analysis shows that the interbasin water transfer project will reduce downstream Aksu River runoff. Different diversion scenarios produce varying degrees of negative impact, particularly during spring and summer when agricultural irrigation demand is high. Summer shows the highest sensitivity, with the largest reduction in downstream runoff (26.36%) when Sary-Jaz River inflow decreases by 30%. Winter shows the lowest sensitivity, with only a 0.77% reduction when inflow decreases by 30%.

Annual-scale analysis reveals that the project will also reduce downstream Aksu River runoff. A 10% reduction in Sary-Jaz River inflow will decrease downstream runoff by 6.89%, while a 30% reduction will decrease it by 20.72%. As water diversion increases, downstream runoff continues to decline.

6. Discussion

From 1958 to 2015, the Sary-Jaz River exhibited significant interannual runoff increases, with significant trends in spring and winter and non-significant trends in summer and autumn. This runoff increase is likely caused by climate warming accelerating glacier and snowmelt in the upper Aksu River Basin. Previous studies have shown that temperature contributes significantly to runoff increases in the Aksu River Basin, and climate change is the primary driver of increased runoff in glacier-fed rivers. From a short-term perspective, increased Sary-Jaz River runoff helps alleviate water use conflicts among industry, agriculture, and ecosystems in the lower Aksu River Basin. However, long-term climate warming will reduce water storage, leading to overall runoff decline and intensifying water scarcity in the Aksu River Basin.

This study has several limitations and uncertainties. Due to the lack of runoff data for the Sary-Jaz River Basin, data from the Xiehela station on the Kumalak River were used as a proxy, which may introduce errors affecting result accuracy. Additionally, this study employed a simple linear method to simulate runoff between the Sary-Jaz River and Aksu River main stream, while assuming a constant runoff coefficient for the Toshkan River, which may also introduce errors. Future research should incorporate hydrological models tailored to the study area characteristics for more in-depth investigation.

7. Conclusions

Based on runoff data from the Aksu River Basin, this study quantitatively analyzed runoff variation characteristics of the Sary-Jaz River and impacts of different development scenarios on downstream Aksu River runoff. The main conclusions are:

1) From 1958 to 2015, annual runoff in the Sary-Jaz River showed a significant increasing trend at a rate of 0.0231$\times10^{8}$ $m^3 \cdot a^{-1}$. Intra-annual distribution varied considerably, concentrated in July–August. Average runoff increased significantly in spring and winter, and non-significantly in summer and autumn. Interdecadal analysis revealed that 1958–1959 was a relatively dry period, 1990–1999 was a relatively wet period, and other periods were normal.

2) Kyrgyzstan's interbasin water transfer project will negatively impact Aksu River runoff. Seasonal-scale analysis shows the project will reduce downstream runoff, with summer showing the highest sensitivity and largest decline (26.36% reduction when Sary-Jaz inflow decreases by 30%). Winter shows the lowest sensitivity (0.77% reduction under the same scenario). Annual-scale analysis shows the project will reduce downstream runoff, with reductions of 6.89% and 20.72% under 10% and 30% inflow reduction scenarios, respectively. As water diversion increases, downstream runoff continues to decline.

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Table 1 Characteristic parameters of the main tributaries of the Sary-Jaz River

Figure 1 [Figure 1: see original paper] Sketch map of the upper Aksu River Basin

Table 2 Basic information of major hydrological stations in the Aksu River Basin

Figure 2 [Figure 2: see original paper] Schematic diagram of water diversion route may be proposed

Table 3 Seasonal variation of runoff in Sary-Jaz River from 1958 to 2015

Table 4 Interdecadal variation of runoff in Sary-Jaz River from 1958 to 2015

Table 5 Multiple linear regression equations of the runoff in Sary-Jaz, Aksai and Aksu Rivers

Figure 3 [Figure 3: see original paper] Characteristics of annual and monthly runoff changes in Sary-Jaz River

Table 6 Sensitivity analysis of runoff in lower Aksu River on annual and seasonal scale to the Sary-Jaz River runoff reduction

Note: Figure translations are in progress. See original paper for figures.

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