Visiting Fellow Program

Water-Food-Energy Nexus: Transboundary Cooperation under Climate Change

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Abstract

In the context of global climate change, transboundary river basin management has become a critical challenge, particularly for upstream-downstream countries. This study focuses on the Irtysh River Basin (IRB), assessing the "Water–Food–Energy" (WFE) nexus and its implications for sustainable development and transboundary cooperation. By integrating climate modelling and sectoral analysis, this study investigates the basin's WFE nexus profiles and responses to climate variability.

Analysis of 20 years of hydrological data reveals temporal heterogeneity in water flows, with downstream areas experiencing greater water scarcity. Temperature trends across all sub-basins show an average increase of 0.65°C since 2000, with the most significant warming observed in upstream regions. The drought conditions in 2022 and 2023 further emphasize the vulnerability of the basin to climate change.

A comparative analysis highlights varied regional responses within the region. In the upstream Altay region of Northwest China, agricultural productivity experienced rapid growth from 2007 to 2018. Crop patterns shifted toward less water-intensive crops, accompanied by notable improvements in water-saving practices, which enabled the conservation of 269 million m^3 of water between 2014 and 2018. The region also diversified its energy mix, significantly increasing the share of wind and solar power while reducing hydropower dependence. Downstream in East Kazakhstan, agriculture showed a slight diversification, although it remained vulnerable to weather variability. Energy production continued to rely on fossil fuels, with limited research on the climate impacts on hydropower generation. The study emphasizes the need for more comprehensive data on water availability, water quotas, and agricultural consumption in downstream regions to support comparative studies.

The findings highlight the importance of integrating WFE nexus strategies in transboundary river basin management. The Altay region demonstrates how responsible upstream resource management can sustain ecological integrity while supporting socio-economic development. In addition, the Belt and Road Initiative offers new opportunities for institutional innovation, prioritizing green energy and optimized water resource management.

Finally, the study advocates for the adoption of an integrated river basin management framework under a market mechanism. This approach can enhance scientific and standardized research on transboundary rivers, reduce information asymmetry, and alleviate cooperation pressures between upstream and downstream stakeholders, thus enhancing transboundary cooperation.

Keywords: climate change, Water-Food-Energy nexus, transboundary cooperation, Irtysh River Basin

Table of Contents

1. Introduction

As economic progress continues to rely on the availability of water, food, and energy resources, a holistic approach to managing their interactions has become increasingly important. Since the Bonn Conference, the water-food-energy (WFE) nexus perspective has provided a valuable lens through which policymakers and researchers can examine these complex relationships across various spatial and temporal scales (Hoff, 2011; Perrone & Hornberger, 2016; Radmehr et al., 2021). By addressing the interactions between water, food, and energy systems, this approach offers strategies for mitigating tradeoffs and ensuring sustainable outcomes (Daher & Mohtar, 2015).

Scholars internationally have conducted nexus research on various aspects including the concept of WFE relationships (Zhang et al., 2018), and theoretical analytical frameworks (Simpson & Jewitt, 2019). Some studies, based on the perspective of cross-border WFE cooperation, have revealed that cooperation between nexus sectors can not only bring environmental, economic, and regional integration benefits, but also help alleviate potential conflicts arising from water resource utilization, promoting consensus among countries in the basin (Al-Saidi & Elagib, 2017; McIntyre, 2014). However, these studies rarely explore the adaptive changes in nexus systems under climate change and mechanisms of transboundary cooperation (Dai et al., 2018; Li et al., 2017).

In Central Asia, water resource management, especially within transboundary river basins, has been a significant challenge due to the impacts of climate change. Fluctuations in water availability, driven by changing climatic conditions, have had far-reaching consequences for regional ecology, economy, and international relations (Bernauer & Siegfried, 2012). As such, a comprehensive understanding of the WFE nexus is critical for securing the future of both the environment and economic development in this region (Seidakhmetov et al., 2014).

However, current studies have not systematically revealed the impact of climate change on the WFE nexus relationship (Qin et al., 2022; Sadeghi et al., 2020). Given the complexity of transboundary basins in the Central Asian region, coupled with the impacts of climate change (Umirbekov et al., 2022), the demand for cross-border cooperation is strong, and there is an urgent need for transboundary basin management based on the WFE nexus.

As an important international river in Central Asia, the Irtysh River extends 4,248 km and flows through China, Kazakhstan, and Russia. After merging with the Ob River, it continues its course into the Arctic Ocean. With climate change, the changing dynamics of water flows will exacerbate water scarcity throughout the basin and complicate water resource management along upstream-downstream relations (Huang et al., 2021).

To date, existing studies on the Irtysh River Basin (IRB) have mostly focused on hydrological background, with gaps in analyzing nexus interactions between water, food, energy, and climate (de Queiroz et al., 2016; Duan et al., 2020). These analyses seek local or national solutions, without considering that transboundary basin management and cooperation could offer basin-wide solutions (Sadeghi et al., 2020).

Scholars have raised concerns about the future of the IRB, particularly the impacts of climate change (Padalko, 2021) and increasing water consumption (Zhiltsov et al., 2018), as both may change the ecological functions of the river and affect demands in the basin. To address these challenges, Hülsmann et al. (2019) argued that transboundary water resource management should comprehensively consider the interlinkages between water-related sectors. Building on this, Qin et al. (2022) proposed an evaluation framework for the WFE ecology system in Central Asia, analyzing the relationships between energy, food production, and environmental degradation of water resources.

Despite these efforts, there is a clear need for further research to develop robust adaptation strategies in the face of changing climate conditions throughout the basin. Improving transboundary cooperation among upstream-downstream countries would play a crucial role in enhancing both economic and environmental sustainability (Purwanto et al., 2021; Ravar et al., 2020).

2. Irtysh River Basin

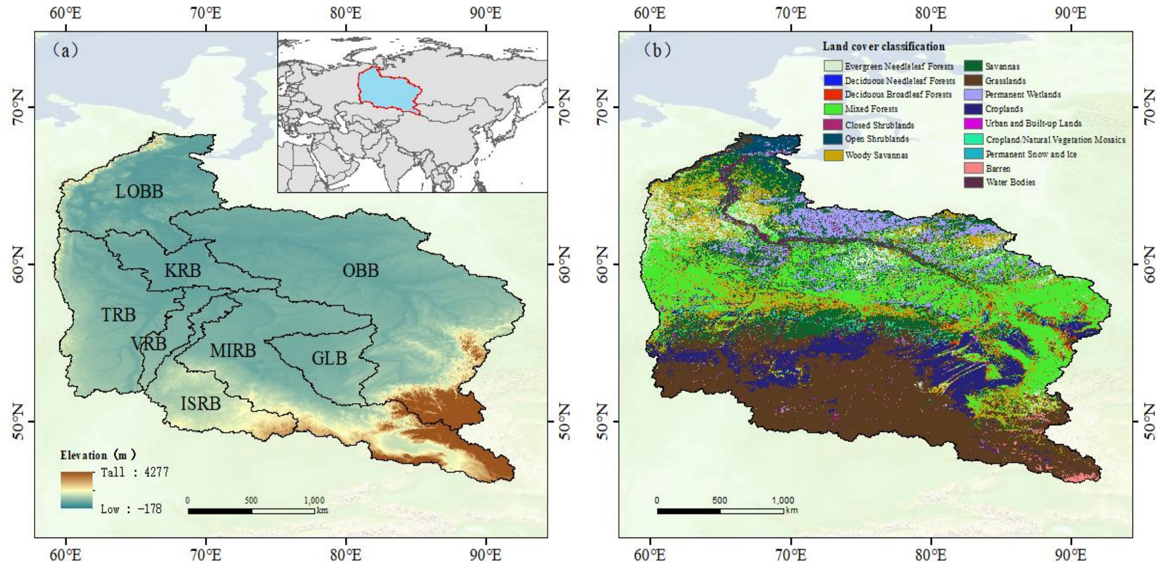
The IRB covers an area of approximately 165 ×10^4 km^2, spanning parts of Mongolia (<1%), China (2.9%), Kazakhstan (53.1%), and Russia (44%), as Figure 1 shows. It supports around 15 million people, with the Irtysh River serving as a crucial resource for ecosystems and socio-economic activities (Radelyuk et al., 2022).

The ecological characteristics of the IRB differ upstream and downstream. Upstream, the basin lies in Xinjiang province in Northwest China and is characterized by desert plains and receding glaciers (Yang et al., 2019). In northeastern Kazakhstan, the climate is arid, with extensive desert regions (Wu et al., 2019). The lower reaches are located in Russia's Western Siberian Plain, where grasslands and cultivated areas are predominant (Gusarov et al., 2018). In addition, economic development and climate change in Northwest China and Central Asia have significantly reduced water availability throughout the basin (Bernauer & Siegfried, 2012).

Historically, China and Kazakhstan have developed a close upstream-downstream relationship through cooperation on transboundary rivers. The establishment of the China-Kazakhstan Joint Commission in 2003 became a key platform for transboundary cooperation. Between 2003 and 2015, 12 meetings were held, in which significant progress was made leading to essential agreements. The two countries also initiated technical collaboration, resulting in the drafting of the *Agreement on Water Apportioning in Transboundary Rivers*, with a working group created in 2014.

Through these efforts, the two countries have effectively maintained the ecosystems of the Irtysh River to ensure sustainable water resource management. This close cooperation between China and Kazakhstan has become a benchmark for transboundary water collaboration in Central Asian countries (Guo et al., 2016). Their joint efforts not only protect shared water resources, but also lay the groundwork for expanding WFE cooperation across the region.

Figure 1. Geographic location of the Irtysh River Basin (a) Sub-basins of the Irtysh River Basin (b) Land covers across the basin



Note: OBB– Ob River Basin, LOBB– Lower Reaches of the Ob River Basin, KRB– Konda River Basin, TRB– Tobol River Basin, VRB– Vagay River Basin, ISRB– Ishim River Basin, MIRB– Middle Reaches of the Irtysh River Basin, GLB– Gor'koye Lake Basin (Huang et al., 2021).

3. Study approach

3.1 Two-step method

This study seeks to understand the regional WFE nexus under changing climatic conditions. It aims to identify adaptive management strategies to enhance regional development and transboundary cooperation in the IRB. The research questions are as follows:

a) What is the status of climate change at the transboundary basin level?

b) What is the regional WFE nexus, and how do these attributes vary under changing climatic conditions across the basin?

c) What adaptation strategies can enhance transboundary cooperation across the basin?

Given the complexity of the WFE at the transboundary watershed scale, it is challenging to establish a definitive system boundary and assemble all the required data for a comprehensive analysis targeting all the issues. However, we remain committed to examining the critical aspects of agricultural production, water, and energy use within the diverse social, ecological, and political contexts of the IRB. Therefore, this approach ensures our study is deeply grounded in the realities of upstream and downstream dynamics (see Figure 2).

Figure 2. Overview of the core study sites

To achieve the research goals, we adopt a two-step methodological approach:

1. Climate trend analysis and modelling:

We first analyze the trends of climate change across the IRB (**Figure 1**). Using a multi-variable regression model, we identify the key drivers influencing water availability at the transboundary basin level.

2. Regional WFE nexus analysis:

We then focus on two sites, namely the Altay region in Northwest China (upstream) and East Kazakhstan (downstream) (**Figure 2**). These regions are selected for their shared and complementary characteristics, which render them ideal for comparative analysis. The hydrological interconnection along the Irtysh River allows us to examine the influence of upstream headwaters on downstream conditions. Moreover, agriculture is the dominant economic and social activity in both regions, so we can evaluate agricultural production alongside its water and energy consumption.

By employing this two-step approach, this study advances interdisciplinary research, offering insights into the broader environmental and socio-economic systems within the IRB.

3.2 Data collection

An interdisciplinary dataset was compiled for the purposes of our study for the eight sub-basins of the IRB, as shown in **Table 1**. For the water system, precipitation, and temperature, streamflow data were collected from various open sources. Energy data was collected from the annual reports of major energy companies and regional statistics.

In addition, data regarding the food system and regional economy were collected, including on crop types and area, crop yield, crop prices, and water quotas from national and regional statistics. Data sources include the "Altay Region Statistical Yearbook," "China Rural Statistical Yearbook," "Statistical Bureau of Xinjiang Uygur Autonomous Region," and "Kazakhstan Bureau of Statistics."

Table 1. Study variables and data sources

Variables	**Open data sources**	**Time span**
Climate		
Sub-basins	HydroSHEDs	
Precipitation, temperature	European Center for Medium-Range Weather Forecasts (ECMWF)	Monthly: 2000–2023
River discharge	ERA5-LAND	Monthly: 2000–2023
Potential evapotranspiration	ECMWF	Monthly: 2000–2023
Agricultural sector		
Sown area, crop yield	Altay Statistical Yearbook, Kazakhstan Bureau of Statistics	Annual: 2007–2018 Annual: 2014–2022
Land use area	MODIS (MCD12Q1)	Annual: 2001–2022
Water sector		
Irrigation water quota in Kazakhstan	Karatayev et al., 2017a	Annual: 2016

Irrigation water quota in the Altay region	Statistical Bureau of Xinjiang Uygur Autonomous Region	Annual: 2012, 2014, 2023
Energy sector		
Hydropower electricity production in East Kazakhstan	Samruk Energy Annual Report	Annual: 2019–2021
Rural electricity consumption in the Altay region	China Energy Statistics Yearbook	Annual: 2007–2018

3.3 Multi-variable regression analysis

To assess the impact of climatic factors on water availability at the transboundary basin level, we employed a multiple stepwise regression model (MSRM) at a 95% confidence level (Yang et al., 2020). Based on Equation (1), we can analyze the correlation between river discharge, precipitation, temperature, and evapotranspiration in each sub-basin. The MSRM equation used was as follows:

$$Runoff=aX1+bX2+cX3 \tag{1}$$

where $X1$ is monthly average precipitation (mm), $X2$ is monthly average temperature (°C), and $X3$ is monthly average potential evapotranspiration (mm). Furthermore, a, b, c are the slope showing the correlation between the climatic factor and river discharge. A slope greater than 0 indicates a positive correlation, while that less than 0 shows a negative correlation.

4. Study results

4.1 Assessing climate change trends

We conducted a statistical analysis to assess the dynamics of river discharge within the IRB. As depicted in **Figure 3**, variations in water flow generation among all the sub-basins indicate that water flows have significant heterogeneity over time. For instance, from 2000 to 2023, a general decreasing trend for river discharge was evident for all sub-basins. In particular, the total runoff of the Tobol River Basin (TRB) has decreased most, by an average of 47% over the past 20 years. It is followed by the sub-basins Konda River Basin (KRB) and Vagay River Basin (VRB), where runoffs for both have decreased by an average of 39% since 2000. These results indicate that water flows at the lower reaches are relatively more scarce.

Climate change trends are also identified for temperature and precipitation during the 2000–2023 period. As **Figure 4** shows, first, our analysis results show an increasing trend for the annual temperature of all sub-basin regions. The average increase is 0.65 degrees across the entire basin as compared to the temperature in 2000. Specifically, the greatest increases in annual temperatures over the past 20 years were evident for the upstream sub-basins—Ob River Basin (OBB), Middle Reaches of the Irtysh River Basin (MIRB), and Gor'koye Lake Basin (GLB)—which rose by 1.12, 0.96, and 0.80 degrees, respectively.

Second, despite fluctuations in annual precipitation, a general decline occurred in all sub-basins from 2000 to 2023, diminishing water availability in the IRB. Notably, the sub-basins TRB, GLB, and VRB experienced the most apparent decreases in annual precipitation, with annual average reductions of 76.5 mm, 61.9 mm, and 60.5 mm, respectively. Hence, the middle- and downstream regions located in Kazakhstan and Russia could receive less precipitation than the upstream regions.

Last, we observed some outliers in the years 2022 and 2023, showing a smaller amount of precipitation than the historical statistics. This indicates the drought conditions in both years, which are consistent with the global trend report (UNCCD, 2023).

Figure 3. Annual total runoff (mm) in the sub-basins of the IRB in the 2000–2023 period

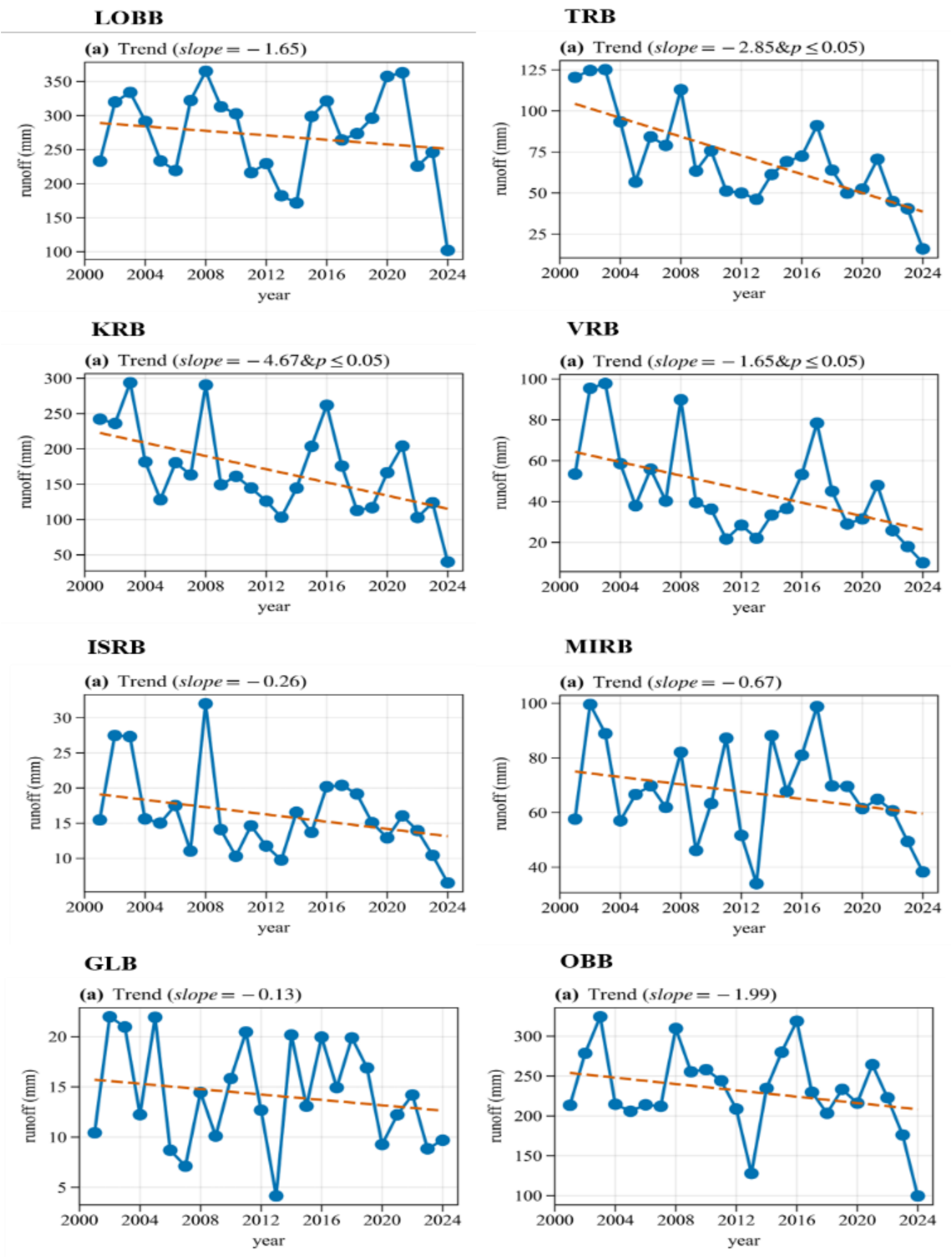
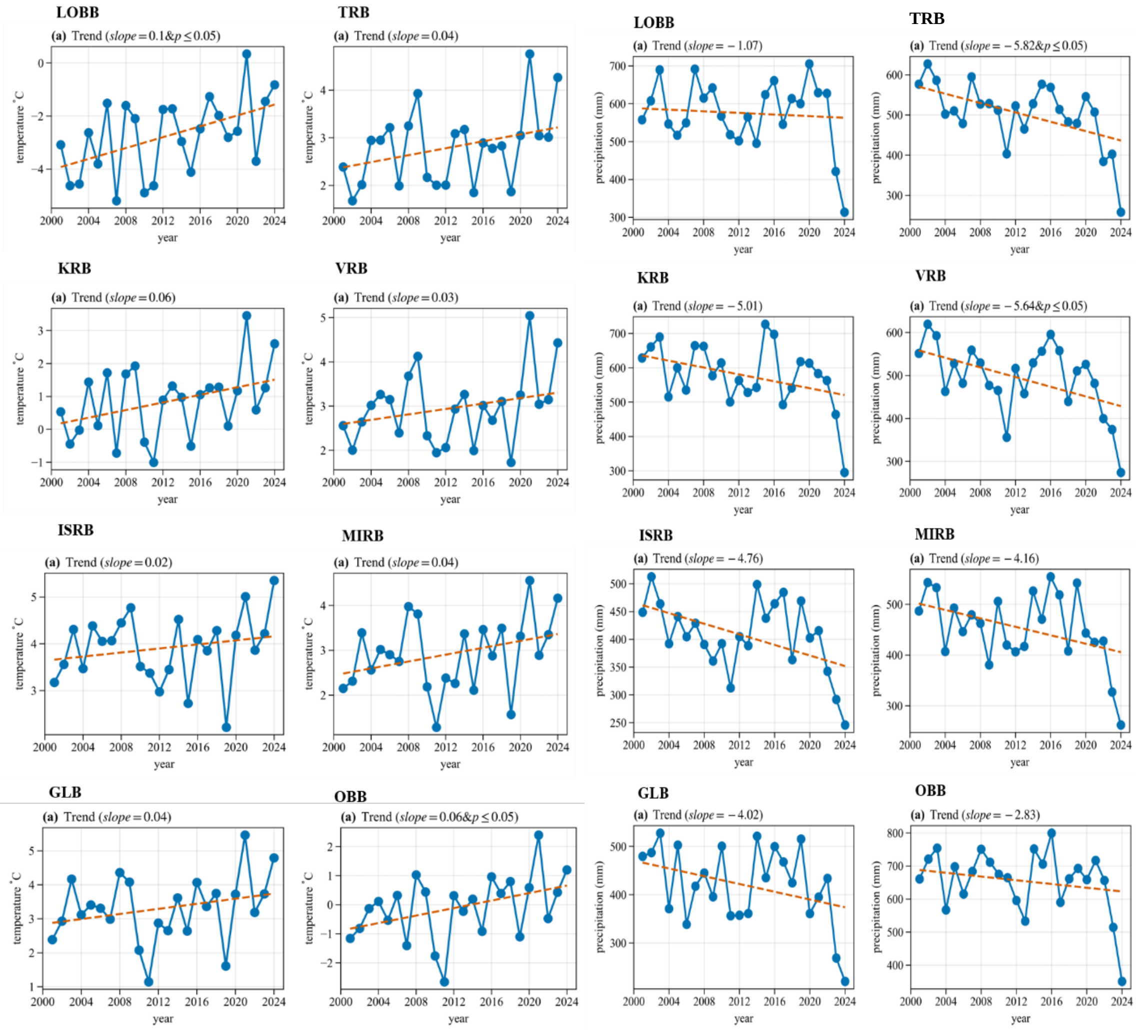


Figure 4. Annual changes in climate factors of temperature (degree) and precipitation (mm) in the sub-basins of the IRB in the 2000–2023 period



4.2 Assessing climatic drivers for river discharge dynamics

Table 2 and **Figure 5** summarize the results of the MSRM, highlighting the spatial variations of climatic variables. For the regression, we used 288 samples of monthly climatic data including of precipitation, temperature, river discharge, and potential evapotranspiration between 2000 and 2023 (**Table 1**). As a result, a high correlation ($p < 0.01$) was found between precipitation and river discharge in the KRB, TRB, and MIRB, indicating that decreased precipitation is likely a primary driver for reducing river discharge in these areas. In addition, temperature was correlated with river discharge trends in the TRB, Ishim River Basin (ISRB), and Lower Reaches of the Ob River Basin (LOBB), showing the strongest association ($p < 0.1$) and indicating that rising temperatures in these sub-basins greatly contribute to reduced river discharge. Furthermore, potential evapotranspiration was highly correlated with river discharge across the eight sub-basins in the IRB, where increases in evapotranspiration likely reduce river discharge due to higher water consumption. In summary, the river discharge in the MIRB, particularly in our core study sites, appears especially sensitive to climatic factors.

Figure 5. Climatic drivers for river discharge in the IRB in the 2000–2023 period

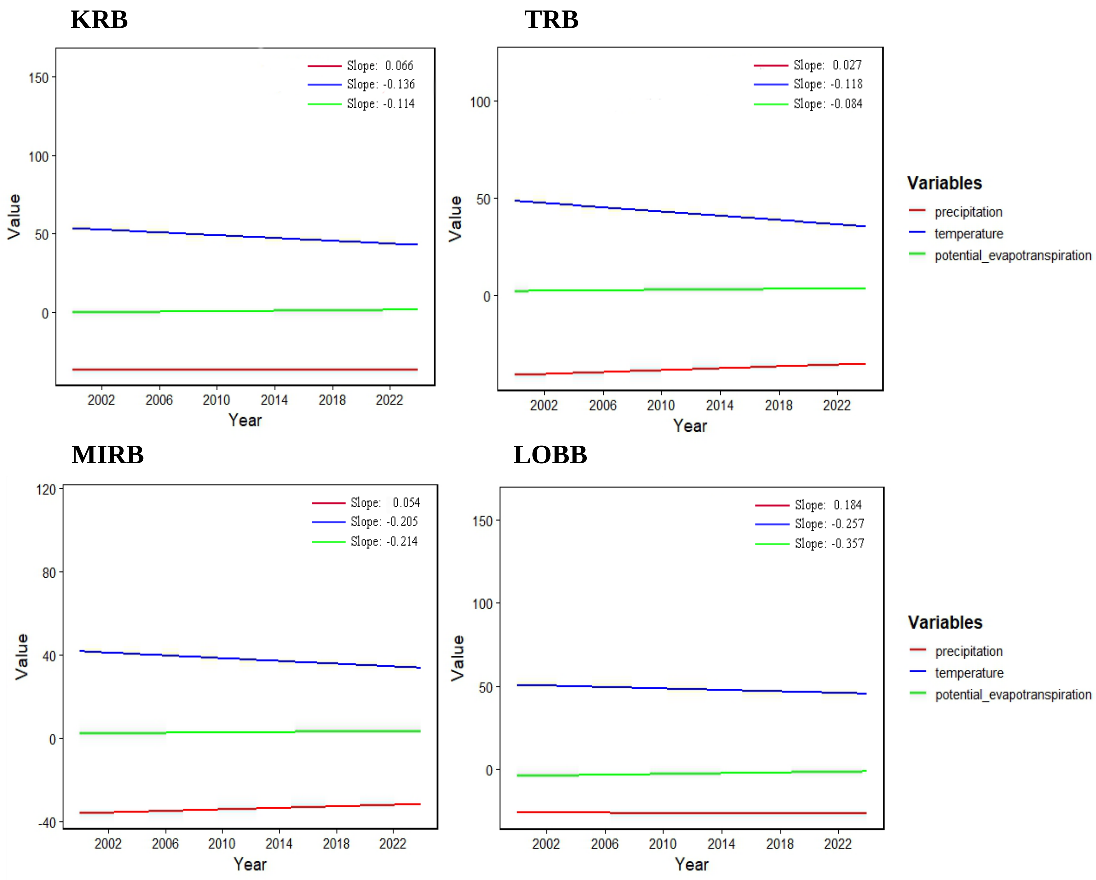


Table 2. **Summary of the multiple stepwise regression results for each sub-basin**

Basin	Factor	coefficient	Constant term	P-value
KRB	precipitation	0.0656^{***}	6.8436	0.001
	temperature	-0.1359^{**}		0.05
	potential evapotranspiration	-0.1143		0
OBB	potential evapotranspiration	-0.2260	10.9719	0
TRB	precipitation	0.0267^{***}	1.9490	0.01
	temperature	-0.1176^{***}		0.001
	potential evapotranspiration	-0.0842		0

VRB	precipitation	0.0190*	2.0007	0.1
	potential evapotranspiration	-0.0244		0
ISRB	temperature	-0.0296*	0.7522	0.1
	potential evapotranspiration	-0.0208***		0.001
MIRB	precipitation	0.0543***	1.0528	0.001
	temperature	-0.2047		0
	potential evapotranspiration	-0.2138		0
GLB	potential evapotranspiration	-0.0066**	0.9407	0.05
LOBB	precipitation	0.1843	3.5508	0
	temperature	-0.2574***		0.01
	potential evapotranspiration	-0.3574		0

Note: * significant at the 10% level, ** significant at the 5% level, *** significant at the 1% level.

4.3 Assessing the regional water-food-energy nexus

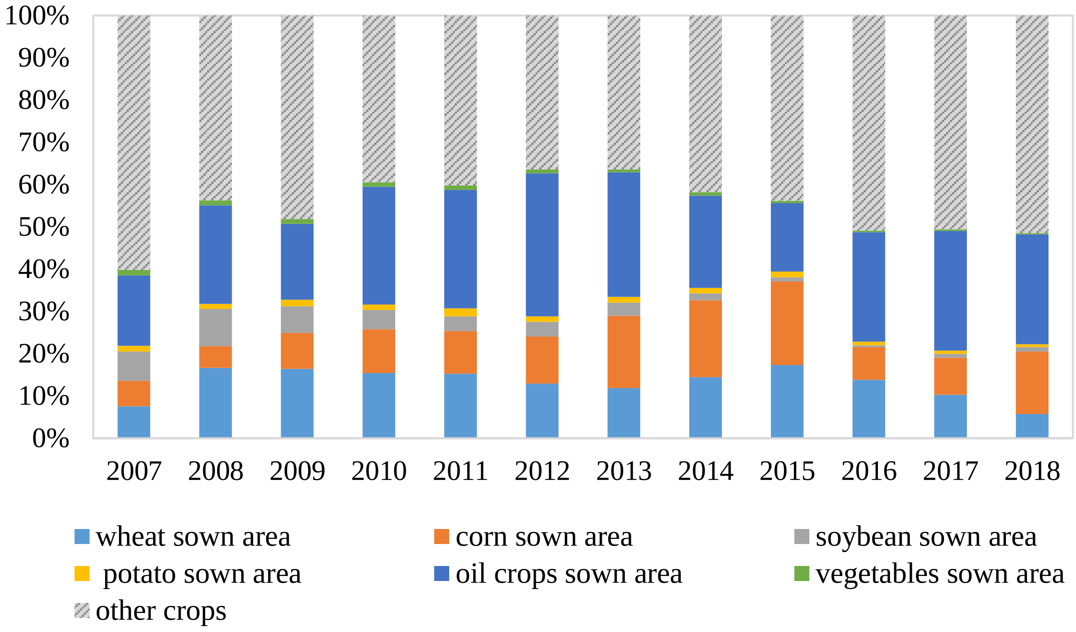
4.3.1 Upstream water-food-energy profile

Food sector

The economic structure in Xinjiang province is characterized by an “oasis economy and irrigation agriculture,” with 95% of total water usage attributed to agricultural water use. Although irrigation agriculture is crucial in this region to sustain agricultural productivity, utilization of the upstream Irtysh River is far less developed than that of its local rivers in Xinjiang province (Hao, 2017).

Based on the statistical data, the primary crops produced in the Altay region (including seven districts) are wheat, corn, soybeans, potatoes, oilseed crops, vegetables, and other crops (**Figure 6**). From 2007 to 2018, the total cultivated area increased by an average of 7%. Among the crops, wheat cultivation had an average annual increase of 25% from 2007 to 2015, followed by a sharp annual decrease of 27% between 2016 and 2018. Similarly, vegetable cultivation saw an average annual decline of 3% over the same period. Cultivation areas for corn, potatoes, and oilseed crops increased by 26%, 5%, and 13%, respectively, in the 2007–2018 period.

Figure 6. Cropping structure in the Altay region in the 2007–2018 period

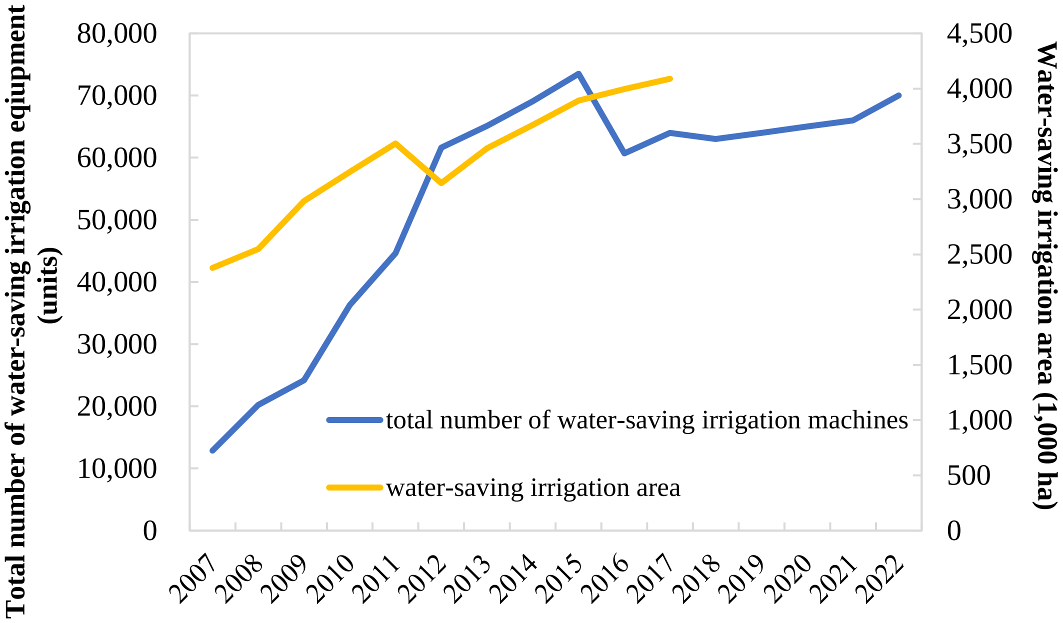


Water sector

Despite expanding agricultural production, the central and local governments are actively promoting water-saving techniques and infrastructure for efficient water use. Since 2008, Xinjiang province has greatly implemented direct subsidies and interest discounts for individual farmers to purchase and invest in agricultural water-saving machines. Local agricultural expansion included initiatives to train farmers in adopting water-saving techniques including mulch, sprinkler, drip, and micro irrigation.

We tracked the availability and adoption of water-saving technologies in the irrigation system over time across Xinjiang province (**Figure 7**). The total number of irrigation water-saving machines increased from 12,868 units in 2000 to 70,000 units in 2022, leading to rapid development of the agricultural water-saving system in this region. Furthermore, the water-saving irrigation area has expanded from 2.377 million hectares in 2000 to 4.089 million hectares in 2018, accounting for 67.4% of the state total cropping area. Here, the drip irrigation area covered more than 98% of the total water-saving irrigation area, while Xinjiang's micro-irrigation area accounted for more than 65% of the entire national total (Li et al., 2024).

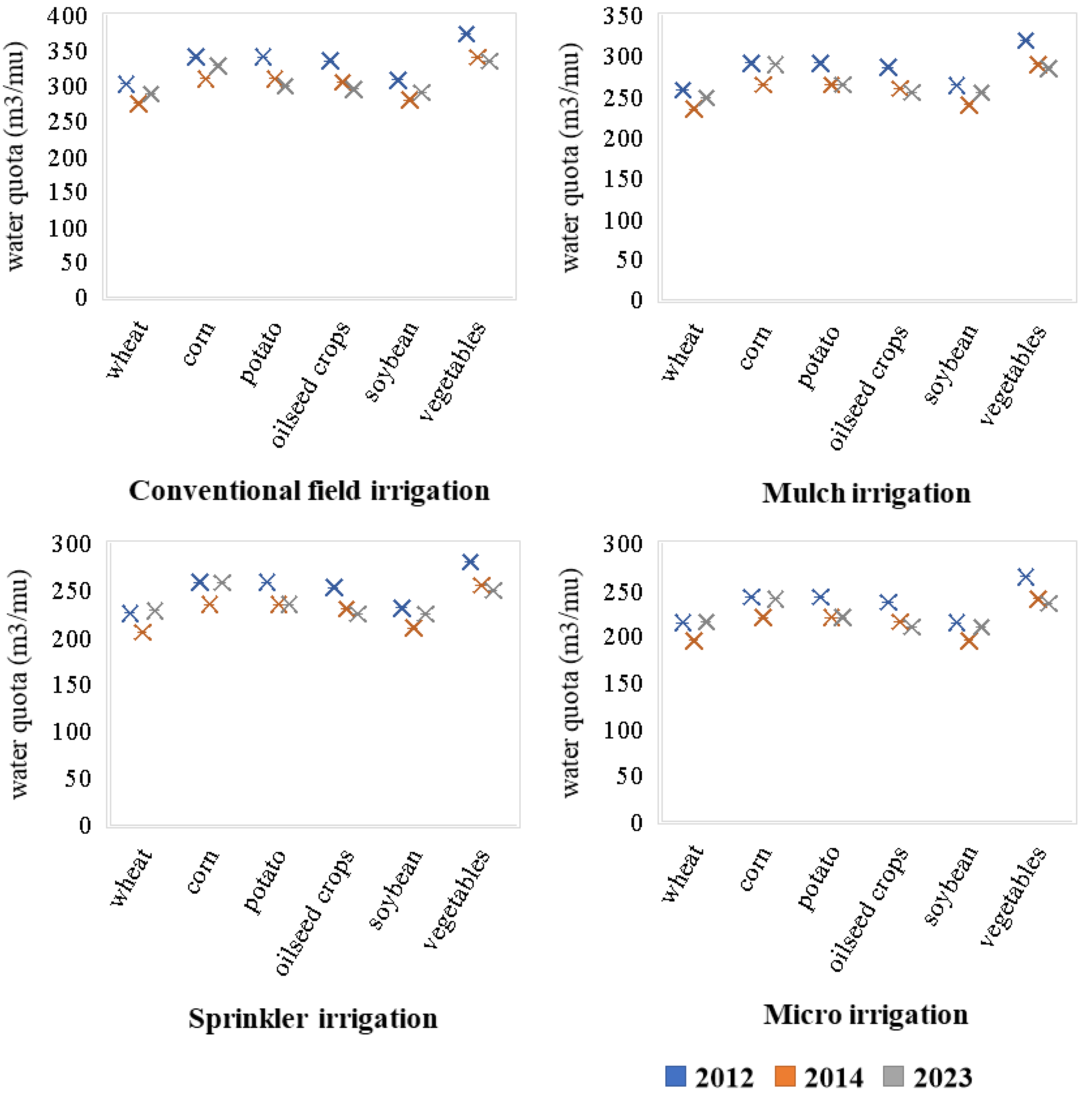
Figure 7. Changes in adoption of water-saving technologies and water-saving irrigated areas in Xinjiang province in the 2000–2022 period



Furthermore, since 2015, following the rapid development of efficient water-saving technologies, the central government started its most severe water pricing reform. Estimates indicate that during the 2015–2022 period, the water utilization coefficient for farmland irrigation in Xinjiang increased from 0.512 to 0.573, and agricultural water use as a proportion of total water consumption gradually declined from 95% to 91%.

Due to the strictest water resource management regulations and improved irrigation systems since 2012, the irrigation water quota was specified for different irrigation techniques in the Altay region (**Figure 8**). As a result, water consumed by conventional field irrigation per mu (1/15 ha) has decreased by approximately 10% for all crops over the past 10 years, with a greater capacity for water conservation and effective utilization.

Figure 8. Adjustment of water quotas for field irrigation in the Altay region


Conventional field irrigation

Mulch irrigation

Sprinkler irrigation

Micro irrigation

Energy sector

With the rapid advancement of agricultural practices, rural electricity consumption has substantially increased in the Altay region. Between 2008 and 2018, electricity consumption in Altay's rural areas rose from 72.93 million kWh to 241.54 million kWh, reflecting an average annual growth rate of 12% (**Figure 9**).

Note that the Altay region is especially endowed with abundant wind and solar energy resources in China, presenting significant potential for green energy development. The wind energy resources in the Irtysh River Valley are particularly notable, as it is one of the nine major wind zones in Xinjiang province, making wind power a key component of the region's green energy portfolio.

By the end of 2022, the total installed power generation capacity in the Altay region totaled 3.8145 million kW, with green energy constituting 92.5% of the total installed capacity. Specifically, wind power accounts for 53.6%, photovoltaic power for 6.3%, and hydropower for 32.6%.

Figure 9. Rural electricity consumption in the Altay region

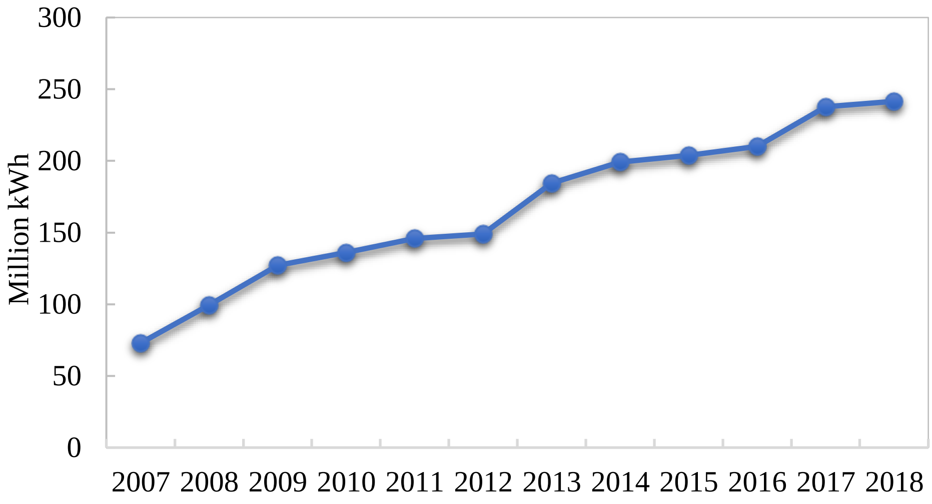
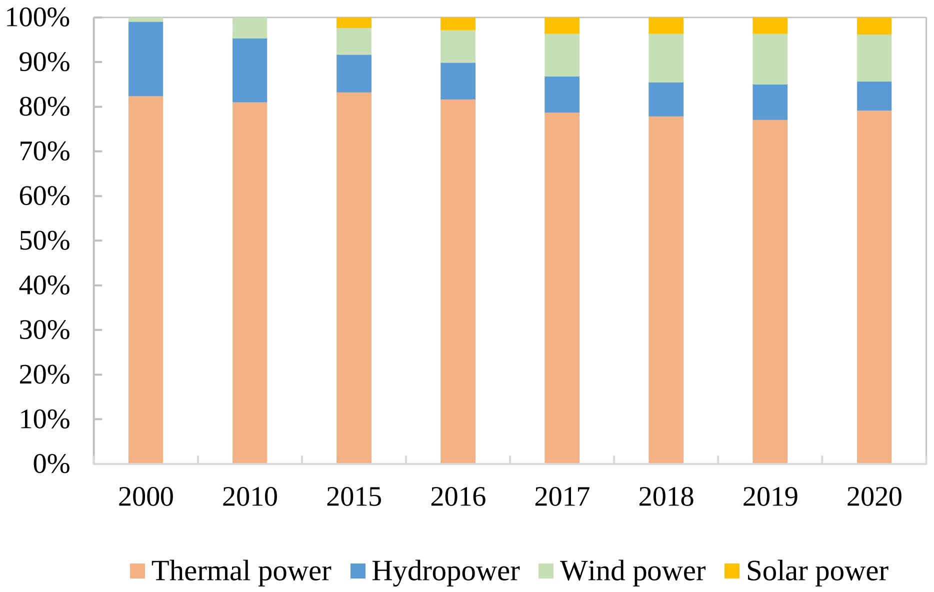


Figure 10. Structure of electricity power generation in Xinjiang province



Furthermore, on May 4, 2023, the Altay region issued the *Medium- and Long-term Development Plan for Clean Energy in the Altay Region*, focusing on the area's key industries and border economy[1]. According to this plan, the Altay region aims to add approximately 21.27 million kW of new wind and solar power capacity. The average cost of green electricity in the region's power market is around 0.35–0.38 CNY/kWh, demonstrating a clear price advantage. With nearly 60% of its annual power output being transmitted outside the region, Altay becomes a significant green energy export base in China and possesses unique advantages in green energy utilization, which aligns with the national goal of "zero carbon emission."

We further analyzed changes in energy structure at the provincial level over the past two decades (**Figure 10**). The data shows that Xinjiang province has continuously promoted the adjustment of energy structure and accelerated the construction of large-scale wind and

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[1] Source: https://newenergy.in-en.com/

photovoltaic power. In general, thermal power is still the main source of electricity generation, accounting for 78% of the total power generation on average. This is followed by hydropower, wind, and solar power generation, which account for 10%, 8%, and 4%, respectively.

Notably, both the volume and proportion of green energy generation, including wind and solar energy, steadily increased in the 2000–2020 period. In other words, despite the rapid increase in total power generation, the region was less dependent on hydropower generation, which decreased from 17% of total power generation in 2000 (the highest percentage thereof) to only 7% in 2020.

Water-Food-Energy nexus

Although agricultural production has rapidly expanded, the Altay region conserved 269 million m^3 of water in the agricultural sector between 2014 and 2018, equating to 54 million m^3 of water conservation per year (**Figure 11**). This was jointly achieved through the implementation of revised irrigation water quotas, enhancement of irrigation infrastructure, and adoption of advanced water-saving irrigation technologies.

Since the Altay region is at the headwater of the sub-basin MIRB, its rainfall fluctuates greatly in the 2014–2018 period. However, the river flows of the Irtysh River stabilized during the same period (**Figure 12**). Thus, to a certain extent, the amount of water conservation due to reduced irrigation water consumption mitigated the impact of climatic drivers (**Table 2**) and contributed to generating downstream water flow.

Figure 11: Crop yield and irrigation water consumption in the Altay region

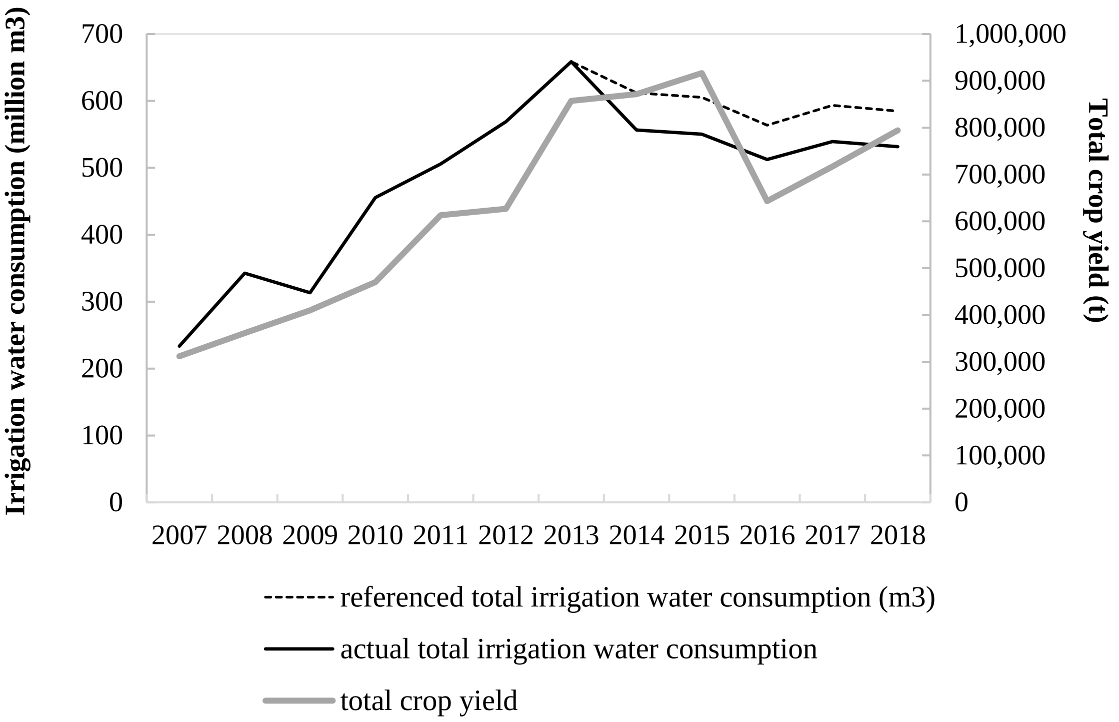
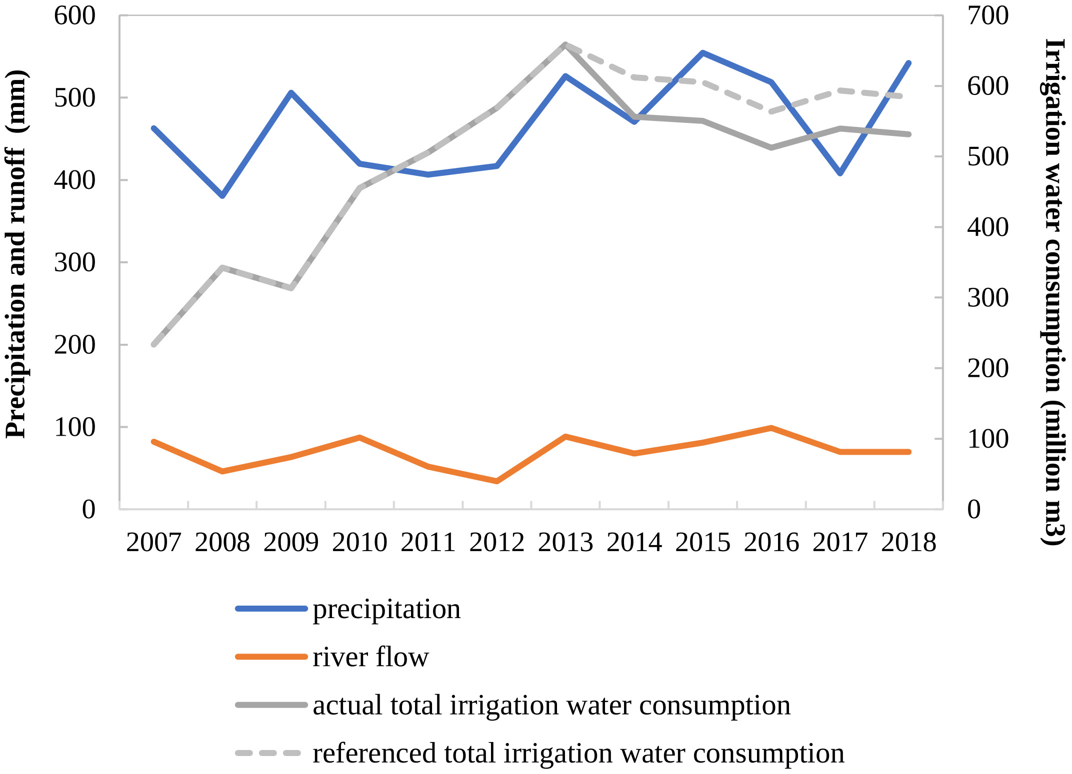


Figure 12. Streamflow and irrigation consumption upstream of the IRB



4.3.2 Downstream water-food-energy profile

Food sector

We analyzed the cropping structure in East Kazakhstan for the 2014–2022 period (**Figure 13**). Specifically, the dominant crops are cereals, which account for 43% of the total sown areas. These areas are sown with wheat, corn, barley, rye, oats, buckwheat, millet, and dried leguminous vegetables. Among the crops, wheat account for 66% of the total cereal sown areas on average. The stability of wheat production is driven by both domestic consumption and exports. Alongside wheat, barley was the second most important cereal crop during this time, which is grown for both human consumption and animal feed. Notably, corn sown areas in 2021 expanded 3.5 times compared with that in 2014.

In addition, vegetables and potatoes were grown in smaller proportions, primarily for local consumption. In contrast, the production of sunflower seeds expanded likely because of the growing demand for vegetable oils and Kazakhstan's efforts to diversify its agricultural output. The share of this crop has increased over time, accounting for 31% of the total sown area in the 2014–2022 period. Given the importance of livestock in East Kazakhstan, forage crops like alfalfa and other grasses occupied a stable part of the cropping structure, accounting for 21% of the total sown area on average.

The crop yield in East Kazakhstan from 2014 to 2022 (Figure 14) shows that grain production remained stable or increased, while the production of oilseeds, vegetables, and forage crops diversified. These changes were influenced by climate conditions, economic shifts, and government policies aimed at improving the productivity and resilience of the agricultural sector.

Figure 13. Cropping structure in East Kazakhstan in the 2014–2022 period

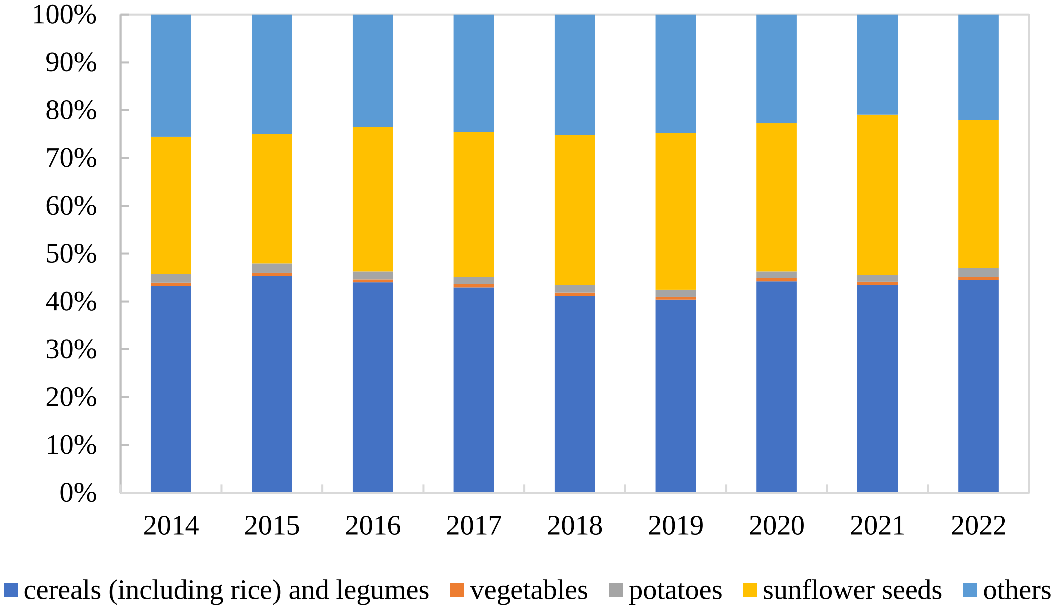
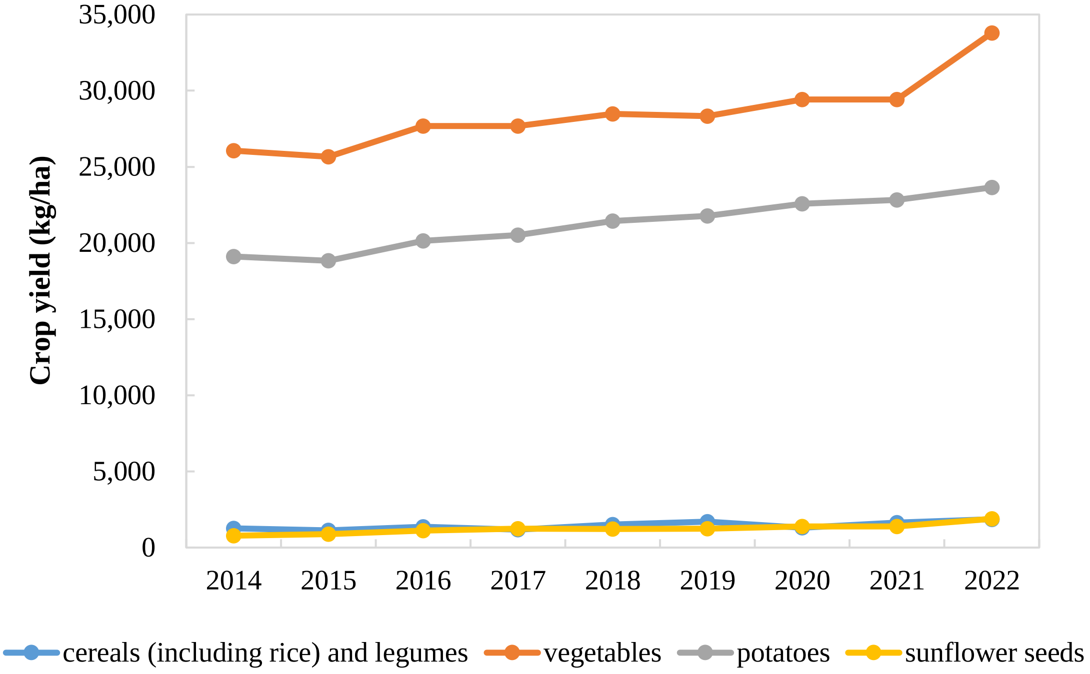


Figure 14. Crop yield in East Kazakhstan in the 2014–2022 period



Water sector

Agriculture consumes 60% of Kazakhstan's total water usage, with irrigated land contributing up to 30% of the country's total crop production. Crops such as cotton, rice, sugar beet, tobacco, grapes, and melons are cultivated exclusively on irrigated lands (NSA, 2016). However, water losses in irrigation networks are severe. In 2022, water losses in irrigated agriculture totaled 65%. The adoption of water-saving technologies remains low, constituting only 3% of the total irrigated area (UN, 2023).

Existing studies show that the demand for water differs between crops and locations. For instance, in South Kazakhstan, the irrigation rate for wheat ranges from 800 to 1600 m^3/ha, for maize it is between 3000 and 4000 m^3/ha, and for sugar beet and perennial grasses it is 5000 to 6000 m^3/ha. In contrast, in Northern Kazakhstan, the water demand for spring wheat cultivation, with a yield of 1.5–2.0 t/ha, is 2–3 times lower than in South Kazakhstan (Rau, 2016). On average, about 3500 m^3 of water is used to produce one ton of crops at the national level (Karatayev et al., 2017a). However, there is no data on water consumption or research defining water quotas in East Kazakhstan.

Energy sector

Kazakhstan's energy landscape is dominated by its substantial fossil fuel reserves. About 90% of electricity generation stems from fossil fuels. In 2022, hydropower accounted for 8.1%, while renewables like wind and solar power plants contributed 2.1% and 1.6% to the energy profile, respectively (IRENA, 2024). Although the country has substantial potential for solar and wind energy, these resources remain underutilized due to insufficient infrastructure and institutional support (Karatayev et al., 2016).

East Kazakhstan houses three major hydropower plants. The Bukhtarma Hydropower Plant has a capacity of 675 MW and a reservoir holding 49,600 million m^3 of water. The Ust-Kamenogorsk Hydropower Plant has a capacity of 331.2 MW. The Shulbinsk Hydropower Plant, located on the middle reaches of the Irtysh River, 70 km upstream from Semipalatinsk, has a capacity of 702 MW. Given the current energy structure, power plant locations, and technologies, water use for energy generation is projected to increase alongside growing electricity demand across all sectors (Großmann & Hohmann, 2021).

Water-Food-Energy nexus

Climate change is anticipated to exacerbate WFE challenges, as more than half of hydropower plants are located in areas that experience high water stress. Projected decreases in precipitation and increasing temperatures are likely leading to water shortages, further straining the production of hydropower (Großmann & Hohmann, 2021). However, despite these issues, studies on the impact of climate change on hydropower generation in Kazakhstan's energy sector remains limited (Karatayev et al., 2017a).

5. Cooperation in transboundary river basin management

Transboundary cooperation depends on mutual trust, effective institutional frameworks, collaborative planning, and fairly sharing ecological and socio-economic benefits and costs (UNESCO, 2009). Building on trends in transboundary water allocation, many studies have examined related theories and mechanisms, providing valuable experiences and lessons for transboundary basin management (Liu et al., 2019; Wu & Tan, 2018).

5.1 Market-based mechanism for transboundary basin management

A new mechanism of transboundary basin management is Payments for Ecosystem Services (PES), which adheres to the principle of “benefits sharing and joint responsibilities” among upstream and downstream stakeholders. It is essential to enhance compensation among different regions within the basin to form a positive interaction where upstream ecological protectors provide ecosystem services and downstream beneficiaries purchase and pay for ecological protectors, thus motivating them to enhance their ecological protection efforts.

Another approach could be inspired by examples from the European Union (EU) (Kliot et al., 2001). In the EU, intergovernmental water commissions manage shared water resources within an international framework. The EU's policies on water, energy, and food management are designed to be inclusive, ensuring equal treatment along upstream and downstream states. This directive supports cooperation and agreements based on shared benefits and considers each river basin as a single geographic and hydrological unit, promoting integrated management (EC, 2000).

Furthermore, the Integrated River Basin Management (IRBM) approach offers another model for transboundary basin management (UN-Water, 2008). The IRBM can be applied at various scales, from local to the watershed or large river basins, as well as at the transboundary level. It is particularly important in addressing upstream-downstream interactions, facilitating regional collaboration, and promoting knowledge exchange among multiple stakeholders.

5.2 The Belt and Road Initiative for transboundary water cooperation

On September 17, 2013, Chinese President Xi, during his visit to Kazakhstan, proposed the construction of the Silk Road Economic Belt, which later became known as the Belt and Road Initiative (BRI). The BRI provides a platform for cooperation regarding water, energy, and infrastructure between China and Central Asian countries, aligning economic cooperation with sustainable resource management.

Transboundary water cooperation is an extension of the BRI framework to address economic growth while ensuring the sustainable management of shared water resources

(Davies & Matthews, 2021). China, the initiator of the BRI, has developed a strategic framework for transboundary water management with Central Asian countries, leveraging an existing international water cooperation mechanism (Liu et al., 2024).

The advancement of the BRI strategy has the potential to support the development of transboundary water-energy projects. For both countries to establish effective cooperative institutions, they need to view water issues within the broader context of social and economic development and seek implementable projects that enhance mutual interest through shared needs and common goals (Wu & Bai, 2020).

5.3 China’s experience in cross-regional water resource governance

Furthermore, the River Chief System (RCS) is an innovative water resource governance framework that originally emerged in China’s river basin management. In 2016, the Chinese government issued a policy document containing “Opinions on Comprehensively Implementing the River Chief System,” thereby establishing the RCS as a national model for water resource management (Ouyang et al., 2020).

By implementing the role of the "river chief" as a pivotal figure, the system breaks through traditional water resource management models, leveraging the authority and resources of higher-level governments to overcome regional barriers, promote the integration of inter-regional administrative resources, and enhance the effectiveness of cross-regional water resource management. Through institutional optimization, the RCS is advanced as a successful model for China’s cross-regional water resource governance, while offering valuable lessons for governance in environmental areas (Wang et al., 2021).

However, integrating relevant software and hardware resources is a crucial task for the RCS, and the platform should be established within basin management institutions. Since institutions are responsible for overall water resource management and protection within the basin, basin management agencies should have a comprehensive understanding and adequate capacity for coordination for the entire basin, while facilitating the supervision and guidance of the river chief's work (Yao et al., 2024). Based on the current literature, no system equivalent to the RCS exists for international rivers. There is also a lack of empirical evidence directly linking the RCS model to transboundary rivers. In addition, the lack of a data-sharing platform in the transboundary river context makes the implementation of the RCS more difficult.

5.4 National water policy in agriculture

Among national water governance strategies, water pricing is considered a significant economic instrument for managing the allocation and conservation of water (Dinar & Saleth, 2005). China's water price for irrigation comprises two parts, namely a basic price charged by area and volumetric price measured by the amount of irrigation.

Although China's water pricing practices have been explored for decades, the water pricing regime in the agricultural sector has been criticized for inadequacies (Wang et al., 2020). One concern is that the current water price for irrigation considers engineering water supply costs rather than water scarcity. Furthermore, it fails to account for farmers' willingness to pay for irrigation water (Huang et al., 2010). Specifically, in Xinjiang province, overall agricultural water pricing deviates significantly from the costs, averaging only about 60% of the cost-based water prices, which results in insufficient incentives for water conservation (Li et al., 2024).

In 2024, China's Ministry of Finance, State Administration of Taxation, and Ministry of Water Resources jointly launched the "Pilot Implementation for Water Resource Tax Reform" to fully leverage the role of water pricing[2]. This reform will replace water resource fees with a tax. The tax will be levied based on the volume of water extracted, with differentiated tax rates depending on water scarcity conditions, the type of water usage, and level of economic development.

In Kazakhstan, low water tariffs contribute to inefficient water use, while financial support for the maintenance and rehabilitation of water infrastructure are inadequate. The current pricing mechanism only partially covers costs, excluding those of constructing and operating irrigation systems, environmental pollution costs, and restoration costs resulting from water overuse (Karatayev et al., 2017b).

Within this context, Kazakhstan is expected to adopt the New Water Code by the end of 2024, which aims to establish a comprehensive national policy for water saving. In addition, the ministry highlighted strengthening transboundary cooperation with neighboring states as a priority[3].

5.5 Green energy cooperation

China's energy cooperation with Kazakhstan emphasizes collaboration with both central and local governments, as well as communities to jointly develop energy-related industrial chains. The cooperative mode in renewable energy has evolved from equipment trade to engineering contracting and the establishment of companies for development and operation (Wang & Zhang, 2024).

In 2023, leaders from China and Kazakhstan signed a Joint Statement underscoring the importance of deepening collaboration in green energy sectors including wind, photovoltaic,

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[2] Source: https://www.gov.cn/

[3] Source: https://astanatimes.com/

and solar power. For example, the Kapchagay 100 MW photovoltaic (PV) power station in the Almaty region, a collaborative investment and technology collaboration between HuanTai Energy and local partners, exemplifies this initiative. The advancement of this project will bolster energy ties between the two countries and support Kazakhstan's energy transition[4].

At the local level, the Altay region outlined a strategy focused on supply-side structural reform, leveraging its unique geographical and resource advantages. This region aims to establish a green energy base, develop a leading area for microgrid technologies, and establish a demonstration zone for carbon peaking initiatives[5].

Moreover, Kazakhstan has committed to the National 2050 Low Carbon Energy Strategy, which aims to increase the proportion of renewable energy generation and expand natural gas usage, reducing by 2030 carbon emissions by 15–25% compared to the level in 1990. Given Kazakhstan's existing water challenges, it is crucial to assess how new energy policies may impact water resources, which requires further investigation (Xu & Wang, 2019).

5.6 Cooperation challenges

While both countries promote open access to information and encourage public involvement in decision making, many studies have indicated that the exchange of water-related data remains inadequate (ADB, 2014; UNDP, 2007). Academic stakeholders in this study have highlighted limited access to government-held data as a major obstacle to conducting in-depth research on transboundary issues.

Consequently, there are significant data barriers. First, to expand the analysis of Kazakhstan, especially the relationship between water utilization and food production, data

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[4] Source: https://www.universalenergy.com/en

[5] Source: https://newenergy.in-en.com/html/newenergy-2423466.shtml

regarding the water quota, crop water consumption, and financing status for water infrastructure are required. Second, the lack of a centralized data system, such as a State Water Department, restricts access to essential data at the state or local level (Sagin, 2016). Our investigation also reveals gaps in agricultural data, such as information on production inputs, and associated costs, leading to inaccuracies in macro-level analysis. Third, energy data may be manipulated for political and economic gain, resulting in the withholding of partial or complete data. Both upstream and downstream countries should prioritize improving their data collection and sharing capabilities (Plengsaeng et al., 2014).

Beyond data scarcity and technical challenges, effective institutional mechanisms—policies and actions across socio-economic and environmental sectors—are vital for policy implementation and for mitigating the impacts of shifts in water availability (Jahanddideh-Tehrani et al., 2021).

To address these challenges, Kazakhstan's government has implemented a series of agricultural reforms in recent years to enhance the sustainability of agricultural production. These reforms include the introduction of modern irrigation systems and water-saving technologies to improve water use efficiency, promotion of drought-resistant and high-yield seed varieties to mitigate the negative impact of climate change on crop yields, and adoption of agricultural mechanization to increase production efficiency and land utilization. Despite some initial success, there are still numerous shortcomings in terms of technology dissemination, financial support, and policy incentives, particularly in the widespread adoption of modern irrigation technology among smallholder farmers.

6. POLICY RECOMMENDATION

Based on the findings of this study, we suggest that the transboundary cooperation between China and Kazakhstan focus on the following key aspects:

First, China should leverage its technological advantages in water resource management to assist downstream regions in upgrading irrigation systems and adopting water-saving irrigation technologies for smallholder farmers, thereby enhancing the agricultural sector's resilience to climate change.

Second, China and Kazakhstan should further strengthen energy cooperation to promote regional energy structure adjustment and economic development at the border. China can continue to increase its technological investment in Kazakhstan, and thereby improve infrastructure and technological innovations for green energy development. This collaboration can contribute to Kazakhstan's structural transformation.

Third, Kazakhstan is actively exploring international markets for high-quality agricultural products. Although agricultural trade between Central Asia and China remains relatively small, it has been growing rapidly in recent years, presenting significant potential for further development. China should deepen its cooperation with Kazakhstan in agricultural trade in alignment with the development of agricultural modernization and industrial advantages.

7. CONCLUSION

This study uses the complex WFE nexus approach to assess the interactions between the reviewed sectors. The results of climate modelling show that water flows in the IRB exhibit significant temporal heterogeneity and are sensitive to climatic factors.

In terms of the regional WFE profiles, agricultural production in the Altay region (upstream) experienced rapid growth between 2007 and 2018. To adapt to a drier climate and improve water use efficiency, cropping patterns gradually shifted toward less water-intensive crops. Despite agricultural expansion, the Altay region still managed to conserve 269 million m^3 of water in the agricultural sector from 2014 to 2018. This achievement was made jointly through revised irrigation water quotas, improved irrigation infrastructure, and the adoption of advanced water-saving irrigation technologies. In addition, this region has actively promoted a transition to a green energy mix and reduced reliance on the generation of hydropower.

In East Kazakhstan (downstream), agriculture remains sensitive to climate variability. Although grain production remained stable, the production of oilseeds, vegetables, and forage crops diversified slightly. These changes were influenced by climate conditions, economic changes, and government policies. Furthermore, Kazakhstan remains heavily reliant on fossil fuels and hydropower, while renewable sources remain underutilized.

Our findings reveal that the synergy within the WFE nexus in the upstream region has contributed to the preservation of the Irtysh River's headwaters, sustaining the runoff against climate change. These results underscore that sustainable water resource development upstream is essential to transboundary water resource management.

The BRI strategy has created opportunities for transboundary cooperation. Unlike traditional government-to-government negotiations, these incremental measures lay a new foundation and consensus for long-term transboundary cooperation between China and Central Asian countries.

Here, establishing a data-sharing platform could promote closer and more effective cooperation in transboundary basin management between China and Kazakhstan. Both countries should ensure the transparency and accessibility of data on the water, agriculture, and energy sector for upstream and downstream stakeholders.

Nevertheless, implementing market-based mechanisms would enable countries to share co-benefits, reducing misunderstandings due to information asymmetry and alleviating pressures in upstream-downstream cooperation, thus paving the way for enhanced transboundary cooperation.

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