RESEARCH REPORT

WATER-AGRICULTURE-ENERGY NEXUS IN CENTRAL AISA THROUGH THE LENS OF CLIMATE CHANGE

Atabek Umirbekov
Almaz Akhmetov
Zafar Gafurov

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Water–agriculture–energy nexus in Central Asia through the lens of climate change

FINAL REPORT

by:

Atabek Umirbekov and Almaz Akhmetov

with contributions from Zafar Gafurov

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Central Asia Regional Economic Cooperation (CAREC) Institute
No. 376 Nanchang Road, Urumqi, Xinjiang, the PRC, Postcode: 830000
f: +86-991-8891151
LinkedIn
km@carecinstitute.org
www.carecinstitute.org

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I. Executive summary

This study examines the climate vulnerabilities of Central Asia's water, agriculture, and energy sectors at province level, using an index-based approach that quantifies their exposure, sensitivities, and adaptive capacities. As a climate exposure metric for the water and agriculture sectors the study uses projections of river discharge and agricultural productivity under RCP 2.6 and RCP 8.5, which are viewed here as 'optimistic' and 'pessimistic' climate scenarios respectively. The sensitivity indicators reflect the degree to which an affected resource is integrated into the economic activity of a province. The energy sector assessment takes into account the challenges associated with meeting projected increases in electricity demand, as well as a global imperative to achieve carbon neutrality by the middle of the century. As a universal barometer for measuring adaptive capacity for all three sectors across the provinces, the study uses proxies of their economic and institutional performances.

The findings suggest that climate change will likely impact water resources in Central Asia, with varying trends across the provinces. The projections indicate that river discharge may decline in the southern river basins of the region, while it may increase in the northern river basins of the region. During the vegetation season, when water is most needed for irrigation in the southern half, river flow shifts may be more dramatic under both climatic scenarios.

Central Asia's strong dependence on water resources is one of the key reasons for its high sensitivity to climate change. This dependence stems from low water productivity, particularly in the southern regions. Transboundary river systems bind downstream countries to the streamflow of upstream countries. Most parts of Turkmenistan, Uzbekistan, and southern Kazakhstan already face water stress, thus any further gap between water availability and demand would exacerbate water scarcity.

The countries should prioritize increasing water use efficiency across the sectors as a means of reducing their sensitivity to the adverse impacts of climate change. This is especially relevant for agriculture, which is by far the largest water consumer. Given the current high level of economic reliance on water resources, promoting alternative, less water-intensive sectors of the economy could be a promising additional adaptation approach. Apart from being a general requirement in the development context, this imperative would also strengthen the structural resilience of local economies to anticipated water stress.

Future variations in water resource availability may have far-reaching effects on other sectors, with agriculture being the main recipient of the respective risks. Climate change will likely have heterogenous impacts on major crops grown in the region, with some crops seeing reduced yields and others may have the potential for an increase in productivity. Nevertheless, even the potential benefits for some of those crop types would be largely inaccessible in the southern part of the region: crop productivity here will be constrained by the projected decline in water for irrigation.

Overall, in many provinces the climate impacts will be magnified by the relatively higher importance of agriculture in the local economy, in terms of share of population engaged and contribution of the sector to regional GDP. Diversification of the economy and the consequent decline in the sector's relative socioeconomic importance may become other important adaptation strategies on a macro scale.

The higher sensitivity to climate impacts is also determined in some subregions by excessive monocropping patterns, when agriculture in a province is dominated by one or a few crops that have either negative prospects under climate change or are water-intensive. Reducing reliance on monocropping and crop structure optimization could diminish the sensitivity of the local agricultural sector to climate change. This needs to be complemented with careful selection and alignment of crop varieties to the changing local climate conditions. The drought-resistance of crop cultivars may become one of the important criteria in cropping decisions.

The transboundary nature of water resources distribution across Central Asia predisposes the countries to a high degree of interdependence and sensitivity to compound risks, when climate-related impacts on water resources transfer the risks to other sectors. Transboundary linkages are particularly strong in south of the region, where the majority of river runoff originates in the highlands of Tajikistan and Kyrgyzstan, while the majority of withdrawals occur in irrigated farmland in downstream Turkmenistan, Uzbekistan, and south Kazakhstan. While the regional coordination of transboundary water management reduces seasonal and annual water supply uncertainty for downstream provinces, it also reduces their sensitivities and increases overall capacity in the region to adapt to long-term changes in water availability.

All countries in the region face a common challenge of maintaining a long-term balance of power demand and supply, given that power consumption is expected to grow by more than half of present generation levels by the middle of the century. The Paris agreement puts an additional burden of GHG emissions reduction, particularly on Kazakhstan, Turkmenistan, and Uzbekistan, where power generation is far more carbon-intensive. This race for power security is compounded in the majority of countries by the high-energy intensity of GDP. While the southern areas of the region are more sensitive to long-term mismatches in power supply–demand, the findings show that many provinces in Kazakhstan are equally vulnerable.

High energy and carbon intensity of the Central Asian economies therefore poses risks to long-term electric power security. Improving the economic efficiency of energy use appears to be a cost-effective first step. Many provinces in the region should also prioritize development of less energy-hungry economic sectors. Nonetheless, albeit costly one, large-scale adoption of renewable energy sources appears to be an unavoidable necessity.

Long-term electric power security of the countries could also substantially benefit from multiple advantages emerging from regional cooperation, in terms of the lower economic cost of electricity and a greater flexibility to curb GHG emissions. As exemplified, cooperation improves the diversity of power supplies on a regional scale, which is another important element of energy security. It could also establish favorable conditions for exploiting the yet untapped potential of renewable sources in the region, which includes the large hydropower potential in the south.

The study used GNI per capita and the government effectiveness (GE) index as proxies for adaptation capacity across Central Asian countries and provinces. Because of the high costs associated with both the adaptation to and mitigation of climate change, lower-income provinces in the region will bear a disproportionate share of the economic burden. Therefore, international development finance will be necessary to strengthen the climate resilience of the Central Asian states. However, resource mobilization alone is unlikely to be sufficient for adaptation. Both the central and local governments should continue to build their capacity in designing and implementing sound sectoral policies.

II. Introduction

Background

In 2020 the Central Asian Regional Economic Cooperation Institute (CAREC Institute) concluded a study 'Climate Insurance, Infrastructure, and Governance in the CAREC Region,' which evaluated the main climate change challenges in the CAREC region through the lens of water–energy–food nexus, economic and financial aspects, and governance. One of the deliverables of the project included a framework developed for the assessment of climate vulnerability on a regional level across the CAREC members, which was applied to estimate disparities among the countries in climate-induced water stress. This section summarizes key findings from the project's first phase and updates them with new insights about the region's interconnected water, agriculture, and energy issues in the Central Asian states—namely Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. In this way, the section outlines the main imperatives for the further development of the multisectoral vulnerability assessment in the region.

Water and agriculture sectors of Central Asia in the face of climate change

Central Asia is a global hotspot for long-term climate trends, having experienced a substantial increase in temperature over the last century (Haag, Jones, and Samimi, 2019). However, it is projected that the region will see more significant seasonal and geographic variations in temperature and precipitation, affecting a variety of natural and climatic factors upon which the socioeconomic systems of the region currently rely.

> *The expected climate impacts will exacerbate the water scarcity already observable in the southern part of the CAREC region, and may intensify the intrasectoral competition over water resources in and among the Central Asian states even further. Magnified by increased water withdrawals provoked by such factors as growth of population, increasing higher irrigation water requirements, the water supply–demand imbalances will likely prevail across a larger part of the region, putting most of the CAREC states in the list of high and extremely high water stress countries in the world. Most types of agricultural activity in the region will be at the frontline of expected climate impact.*
>
> CAREC Institute (2020)

In particular, climate change may dramatically alter hydroclimatic conditions, whereas the water resources underpin a wide variety of economic activity throughout Central Asia. Agriculture appears as one of the most directly impacted sectors, which employs at present between 8.2 percent and 65 percent of the population (Turkmenistan versus Tajikistan) and contribute to between 5 percent and 23 percent of GDP (Kazakhstan versus Tajikistan) (ADB, 2017a). Given the extent of anticipated climate change and their greater importance to national income and employment, the water and agriculture sectors are among the most vulnerable in the CAREC region to climate change (CAREC Institute, 2020).

Challenges to assure power electricity security in the long term

Central Asia is endowed with abundant fossil fuel deposits, yet these reserves are distributed inequitably throughout the region. Kazakhstan, Turkmenistan, and Uzbekistan are important oil and natural gas exporters, while Kyrgyzstan and Tajikistan rely heavily on their hydropower potential. This gap in primary energy resources also results in a significant divergence in the energy intensity of the respective economies. Until now, Kazakhstan, Turkmenistan, and Uzbekistan have been among the world's top countries in terms of energy consumption per GDP, which, among other factors, also indicates low efficiency of energy use (Shadrina, 2019).

Despite disparities in primary energy resources, fulfilling the ever-growing demand for electricity in a sustainable and cost-effective manner remains a shared concern for all five Central Asian countries. To a greater extent, this increase in power demand is thanks to population growth and the promotion of new manufacturing sectors, which exceeded the pace of infrastructural upgrades (ADB, 2013). Most generation capacity in the region has beyond 40 years of operation, and power transmission is characterized by comparatively high loss. Except in Kazakhstan, electricity tariffs in all the countries hardly cover generating and transmission costs, jeopardizing the sector's financial viability and impeding technical upgrades and expansion (Boute, 2019).

Nonetheless, it is expected that the power demand in the region will continue to grow rapidly in the long term. The projections show that the total regional electricity production in Central Asia will have to increase by 66 percent by 2050, although this increase will not be homogenous across the region (IEA, 2021b). Climate mitigation becomes a complementary concern for Central Asian countries in terms of maintaining a long-term energy demand–supply balance. Each of the five states is a signatory to the Paris Agreement and has established national targets for carbon reduction. This implies considerable capital expenditure for power system transition, particularly in Kazakhstan, Turkmenistan, and Uzbekistan (ADB, 2017b), where existing power generation capacity is mostly reliant on fossil-based thermal power plants.

Water–agriculture–energy nexus in Central Asia and regional cooperation

During the Soviet era, the Central Asian nations were connected by a shared water–power system, in which water and electricity supplies from upstream states were compensated for by energy supplies from downstream states during the vegetative season. This cooperation has been largely interrupted in recent decades as countries pursued self-sufficiency strategies in water and energy, which eventually resulted in disagreements about equitable exchanges. As a result, the region's total energy trade fell by more than half during the 1990s and countries began looking for ways to export seasonal electricity surpluses rather than import them (Figure 1).

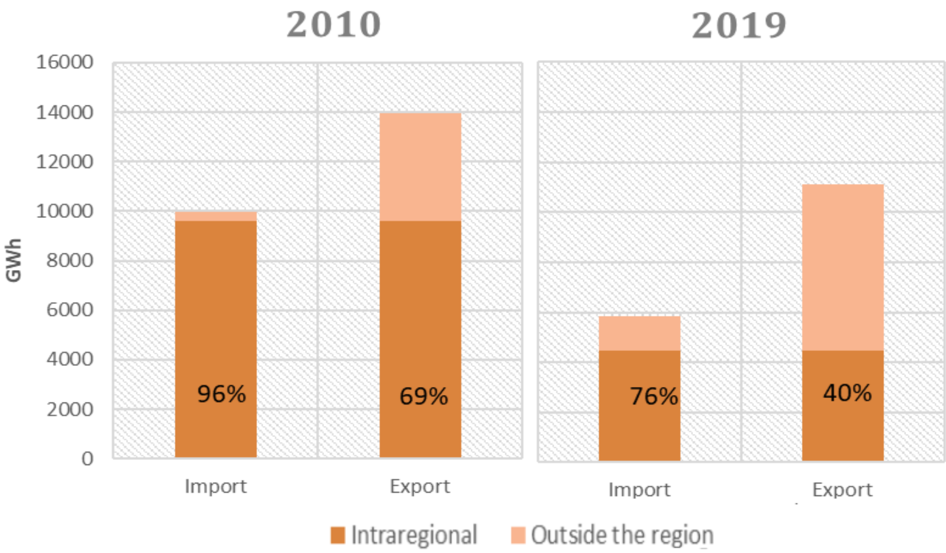


Figure 1. Transfers of electricity across Central Asian countries in 2010 and 2019

Source: (KOREM, 2020; IEA, 2021b)

Overall, this situation deteriorated the electricity demand–supply balance, particularly in upstream states, while jeopardizing the water security of downstream states. All prior technical studies conducted by independent parties and multilateral development organizations emphasized the critical role of regional cooperation in ensuring the water and energy security of the Central Asian states (Xenarios, Shenhav, and Abdullaev, 2017; CAREC, 2021; IEA, 2021a). Additionally, increased regional cooperation would result in lower power generation costs and avoid capital expenses for redundant power capacity, as well as giving better options for GHG emission reductions and favorable conditions for the use of intermittent renewable energy sources (World Bank, 2017; Shadrina, 2019).

The benefits of regional cooperation also extend to food security aspects, as food security is not defined simply by crop self-sufficiency on a national level but rather by the ability to meet the demand for food adequately, regardless of where the supply originates from. International trade has been shown to be an important determinant of food security in countries where crop-specific farming is hampered by certain circumstances, such as meteorological conditions (Baer-Nawrocka and Sadowski, 2019). Thus, it is suggested that countries would be better off concentrating their efforts on high value added agricultural production of crops in which they have a comparative advantage owing to climatic and institutional conditions (Lombardozzi and Djanibekov, 2021), while compensating for the deficient production of other crops through international trade.

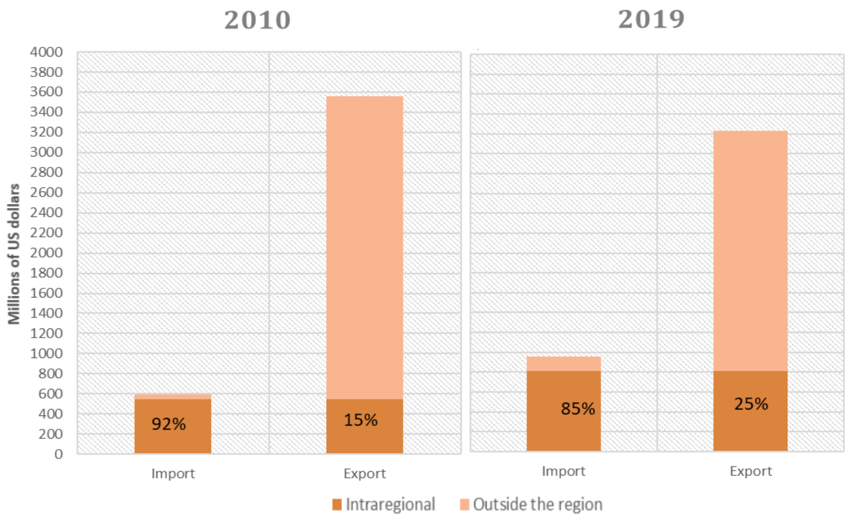


Figure 2. Total trade of agricultural crops (wheat, corn, cotton, rice) and derivative products across Central Asian countries in 2010 and 2019

Source: Simoes and Hidalgo, 2011

Central Asia is a net exporter of agricultural crops and commodities covered by the study, owing mostly to Kazakhstan's relatively significant grain production and Uzbekistan's cotton production. To a greater extent, this includes cross-border trade in wheat and wheat products, with Kazakhstan being the greatest net exporter. Additionally, trade of other crops such as maize, rice, and vegetables increased throughout the region (Figure 2).

Objectives

Addressing the outlined imperatives, this study aims to:

- Extend the climate vulnerability assessment framework to the agricultural and energy sectors of the five Central Asian states: Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan
- Downscale the assessment to smaller geographic units (province level)
- Account for the interconnectedness of water, agriculture, and energy issues in the region and integrate the impact of regional cooperation among the states

The vulnerability index approach for the agriculture sector takes into account the diversity of agricultural activity in the countries (rainfed crop production versus irrigated agriculture), the climate challenges associated with these types of agricultural activity, and the varying degrees of socioeconomic dependence of a province on agriculture.

Given the multifaceted nature of energy systems in the region, as well as the discrepancy in fossil fuel endowment between the Central Asian states, the vulnerability assessment of the energy sector focus on power electricity. Long-term power supply security is a shared challenge for all countries in Central Asia and is a primary focus of the CAREC program as well as other multilateral development organizations engaged in the region.

Methodology

The study employed the methodological approach based on the IPCC framework for assessing climate vulnerability. Accordingly, vulnerability is defined as *the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is determined by the kind, amount, and rate of climate variation to which a system is exposed, as well as the sensitivity and adaptive capacity of the system* (IPCC, 2007). In broad terms, vulnerability can be expressed as a function of potential impacts, as measured by exposure and sensitivity, and a system's adaptive capacity to withstand anticipated impacts. Figure 3 illustrates the structural composition of the framework suggested for the assignment.

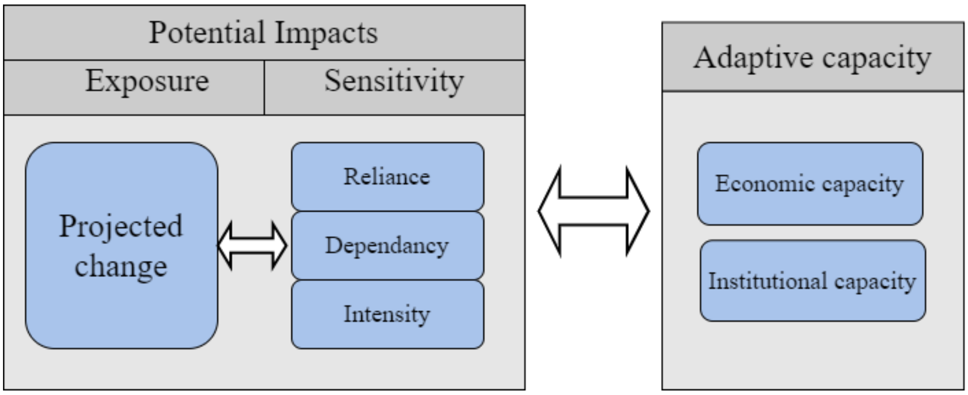


Figure 3. Methodological framework for estimating climate vulnerability

The **exposure component** quantifies the characteristics and amount to which a sector is exposed to significant climatic change. For example, the water sector evaluation focuses on climate-induced water stress, with long-term predicted water supply serving as the primary indication of projected change. Agriculture's vulnerability score considers projected changes in yields of primary crops farmed in the region (wheat, cotton, maize, oil crops, and rice). The energy sector assessment encompasses challenges to meet a projected increase in power electricity demand, given the climate implications for the water and agriculture sectors as well as the stated carbon reduction targets of the Central Asian countries. This study employs projections generated from the latest hydrological and crop modeling research under the two climate scenarios, where RCP 2.6 is regarded as 'optimistic' and RCP 8.5 is considered as 'pessimistic' pathways (see Annex 2).

The **sensitivity component** determines the degree to which a system is affected by climate-related implications. The extent to which expected variations in wheat yields influence a country or a province depends on whether grain production accounts for a sizable portion of a province's economic activity. This can be quantified in terms of the contribution of wheat farming to regional domestic product or the proportion of the population engaged in agriculture, which we consider here as *reliance* indicators. In turn, *dependency* indicators represent the extent to which a country/province is dependent on external systems for a certain resource. For instance, the majority of water resources accessible to the downstream states originate in upstream countries, which may be quantified and factored into the vulnerability assessment using the water dependency ratio. Similarly, intensity indicators quantify the degree to which a resource is integrated into a country's/key province's economic activity. For example, energy consumption per capita or per unit of GDP serves as a proxy for sensitivity to disruptions in the power demand–supply balance. On the other hand, overall improvements in energy efficiency reduce the sensitivity to projected changes in energy supply.

The **adaptive capacity** refers to the system's ability to adapt to the expected climate implications. For all three sectors, the study universally used the same indicators that measure economic, institutional, and human capacity to absorb adverse effects and/or capitalize on any favorable prospects. The economic capacity is represented by GNI per capita as an indicator measuring the state of development and as one of the main criteria reflecting the adaptive capacity of the Central Asian countries. Institutional and human capacity is approximated by using the GE index, which reflects the ability of the states to provide quality public services, to maintain quality civil service, and to design and implement sound policies, and the credibility of government commitment to such policies.

Spatially explicit vulnerability

One of the primary tasks for the projected climate vulnerability index is to provide a regionally distributed overview of vulnerability in order to account heterogeneity of its key components on smaller geographic scales. This was largely accomplished by either utilizing spatially disaggregated data or interpolating country-level estimates to province level as applicable. Thus, the majority of the key variables within the exposure and sensitivity components are estimated at province level (see Table 1). Nonetheless, certain indicators remained aggregated at national level in cases when spatial disaggregation was complicated owing to an absence of supporting data or when the indicators do not conceptually imply spatial distinctions within a country.

Annex 1 and 2 provide an expanded description of the index-based methodological approach and the projections used for estimating changes in water availability and agricultural productivity in the region.

Data

The set of indicators of exposure, sensitivity, and adaptive capacity for each targeted sector are provided in Table 1. Annex 3 provides detailed information on data sources.

Table 1. Indicators used for construction of vulnerability index per sector

	Indicators	Aggregation level
WATER	**EXPOSURE:**	
	Projected change in water availability	Province
	SENSITIVITY:	
	Water withdrawal to availability ratio	Province
	Water consumption per gross regional product (GRP)	Province
	Water dependency ratio	Country
	ADAPTIVE CAPACITY:	
	Government effectiveness	Country
	GNI per capita	Province
AGRICULTURE	**EXPOSURE:**	
	Projected change in crop yields: wheat, cotton, maize, rice	Province
	Projected change in water availability (for irrigated crops)	Province
	SENSITIVITY:	
	Crop-specific area as a fraction of total harvested area	Province
	Share of agriculture in GRP	Province
	Share of population engaged in agriculture	Province
	ADAPTIVE CAPACITY:	
	Government effectiveness	Country
	GNI per capita	Province
ENERGY	**EXPOSURE:**	
	Projected increase in power demand by 2050	Country
	Climate mitigation towards carbon neutrality	Country
	SENSITIVITY:	
	Electricity consumption per GRP	Country
	Carbon intensity of power generation	Country
	Power diversity mix	Country
	ADAPTIVE CAPACITY:	
	Government effectiveness	Country
	GNI per capita	Province

III. Water resources at the frontline of climate change

To estimate the impact of climate change on water availability, this analysis examines the relative change in discharge of Central Asia's major rivers (Figure 4) by 2040-2069 with respect to the 1975-2005 baseline. The global hydrological projections employed by the study suggest that under RCP 2.6 the annual discharge in most considered rivers will likely remain near normal (Figure 5), with the exception of the most southern rivers Murghap and Tedzhen, which may see a decrease, and the most northern basins of Ishym and Tobol, which will likely see a slight increase. The disparity between northern and southern basins in terms of annual discharge may widen under RCP 8.5, although the wider spread of hydrological projections also implies relatively higher uncertainty. According to the RCP 8.5 projections the higher number of rivers located in the domain's southern to central regions may experience a decline in annual river flow.

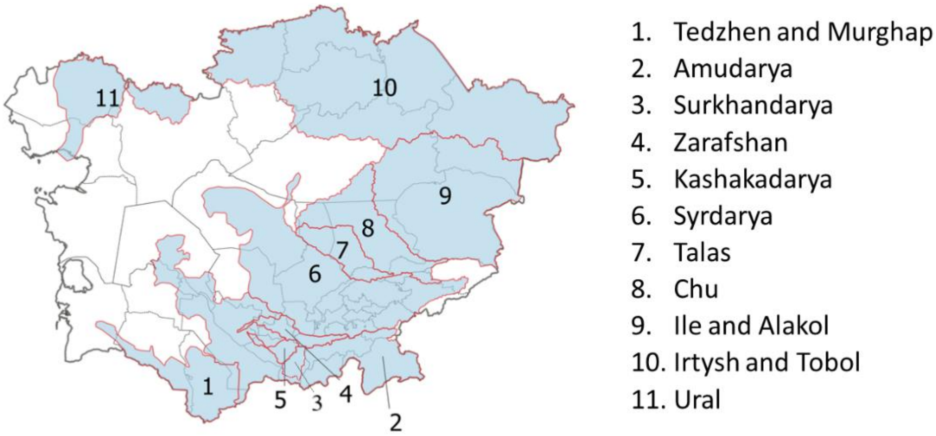


Figure 4. Major river basins in Central Asia

The projected changes in annual discharge indicated in Figure 5 would not, however, occur evenly throughout the months/seasons within a year. The projections indicate that the seasonal distribution of runoff in the majority of rivers in the region will also likely change, with peak flows shifting to earlier months. It is worth noting that irrigated agriculture is the major consumer of water in Uzbekistan, Turkmenistan, and southern Kazakhstan and that, in this sense, it is more important to consider water availability during the vegetation season, which typically lasts from April to September in this part of the region.

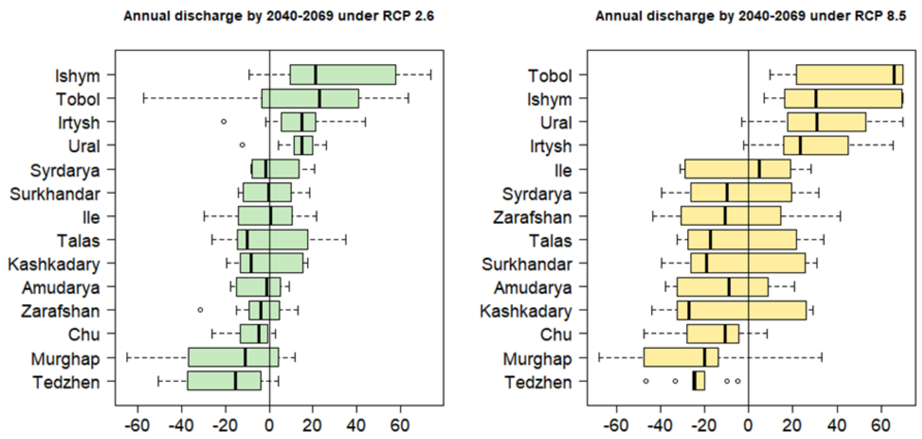


Figure 5. Projected relative change in annual discharge of the major rivers in Central Asia by 2040-2069 with respect to 1975-2005

The hydrological projections indicate a substantially greater disparity in the relative change of seasonal discharge by 2040-2069 among the target basins (Figure 6). Under both climate scenarios, discharge during the irrigation season is anticipated to decrease in almost half the river basins by 2040-2069. In descending order, the Murgap, Tedzhen, Surkhandarya, Kashkadarya, Zarafshan, Talas, and Chu rivers may become the most affected under the RCP 2.6. While the RCP 8.5 projections suggest even larger reductions of the seasonal runoff in those rivers, they also indicate that the Amudarya and Syr Darya rivers may also see a decline in runoff. In contrary, the Irtysh, Tobol, Ural, and Ishym rivers may experience an increase in seasonal runoff. It should be noted that the seasonal discharge projections have a relatively lower degree of uncertainty compared with the annual discharge projections.

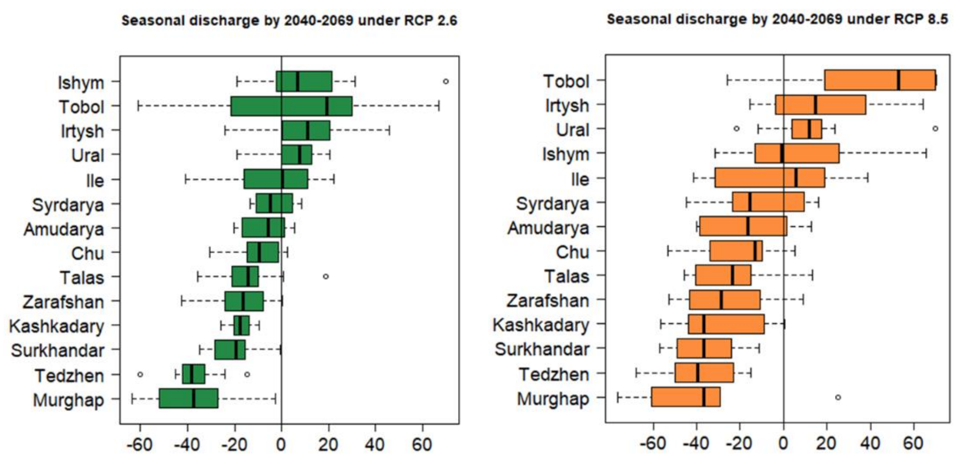


Figure 6. Projected relative change in average discharge of the target rivers during April-September

Figure 5 illustrates how anticipated variations in future seasonal runoff under the two scenarios may change the water availability across Central Asia at province level. The distribution follows an evident north-south pattern, with provinces in southern Central Asia will potentially experience a decline in available water resources on the seasonal scale, while subregions in northern Kazakhstan may see the reverse trend. The Mangystau province in western Kazakhstan is left blank on the map owing to its reliance on a water desalination plant for domestic and industrial water supply and virtually no agricultural use of water owing to absence of crop production.

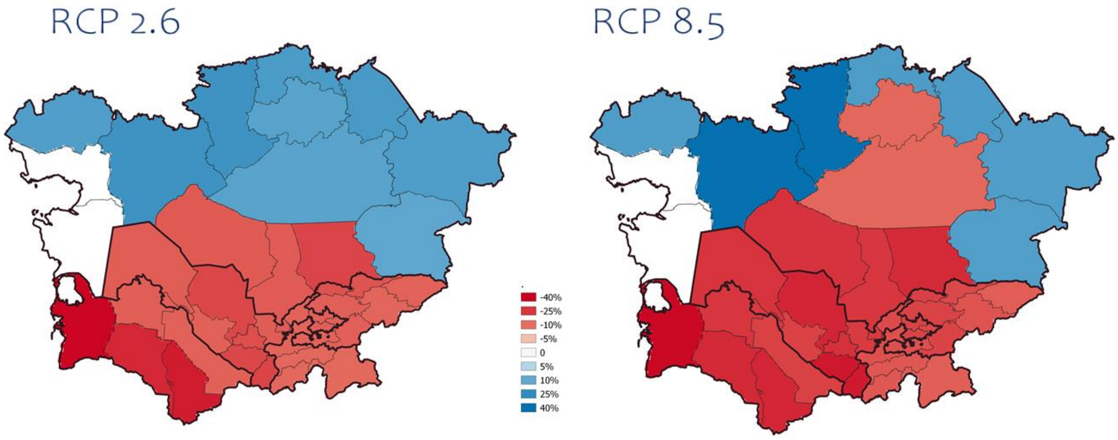


Figure 7. Provinces affected by the projected change in seasonal discharge of rivers

The overall sensitivity to the projected changes in water supply differs significantly between Central Asian countries, owing to their varying degrees of reliance on water resources (Figure 8). With relatively fewer water-intensive sectors and generally more abundant water resources, particularly in the north, Kazakhstan has the region's lowest water withdrawal ratio. On the other hand, owing to the scale of irrigated agriculture in Turkmenistan and Uzbekistan, annual water withdrawals exceed the total annual renewable surface water available. This sensitivity is heightened by the fact that the most of the water resources available to Turkmenistan and Uzbekistan originate from outside these countries.

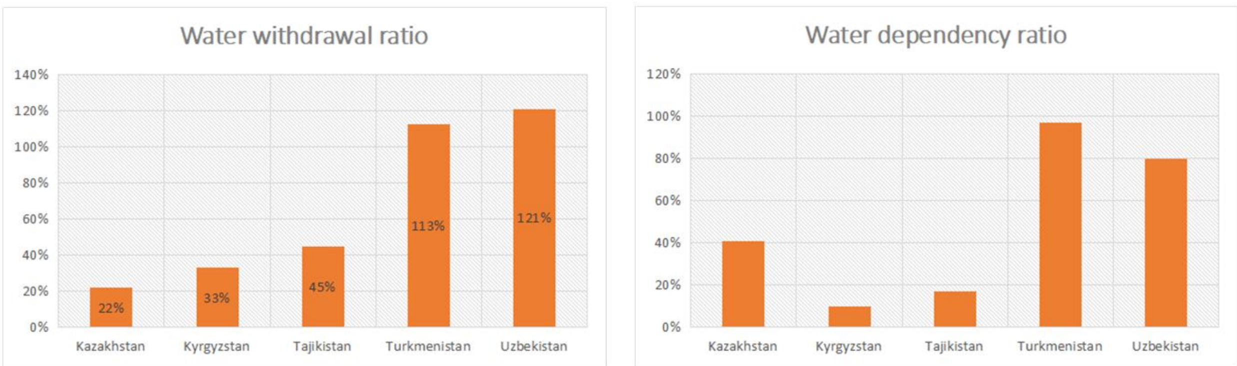


Figure 8. Intensity of water use among the Central Asian states.

Source: (FAO, 2022)

Although the picture is relatively more heterogenous at province level, water intensity per unit GDP follows a similar south-north pattern (Figure 9). Water withdrawals per GRP[1] are considerably higher in most provinces in the south of the domain owing to a greater domination of water-intensive sectors and relatively lower economic output levels.

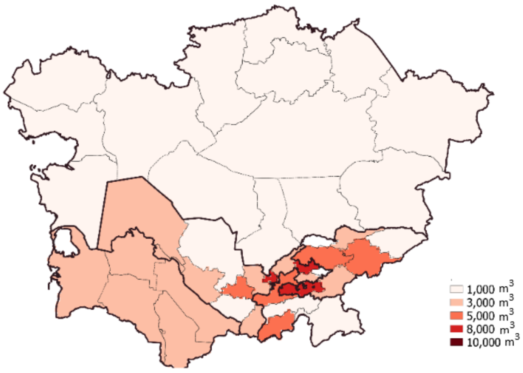


Figure 9. Water withdrawals per unit of GRP

Source: Based on country statistics (GRP) and estimates on total water withdrawals from WaterGAP2c model

Figure 10 illustrates the spatial distribution of relative vulnerability hotspots across provinces in Central Asia in light of expected changes in water availability and their economic reliance on water resources. As a result, the region is correspondingly susceptible in practically all provinces of Turkmenistan and Uzbekistan, both as a result of expected declines in seasonal water availability, as well as higher withdrawal availability and water reliance rates in these countries at present. While Tajikistan and Kyrgyzstan have slightly lower vulnerability scores, they are still expected to face moderate to strong water stress as a result of their inferior adaptive capacities to deal with possible climatic hazards. The south of Kazakhstan, also located downstream of transboundary rivers, appears to be as vulnerable as the regions in Tajikistan and Kyrgyzstan. The overall distribution of vulnerability hotspots by 2050 does not change significantly across the climate scenarios, with the southern half of the domain continuing to face considerably greater risks under both RCP 2.6 and RCP 8.5.

[1] Contributions from the fossil fuel extraction and processing sector were excluded from the GRP calculations

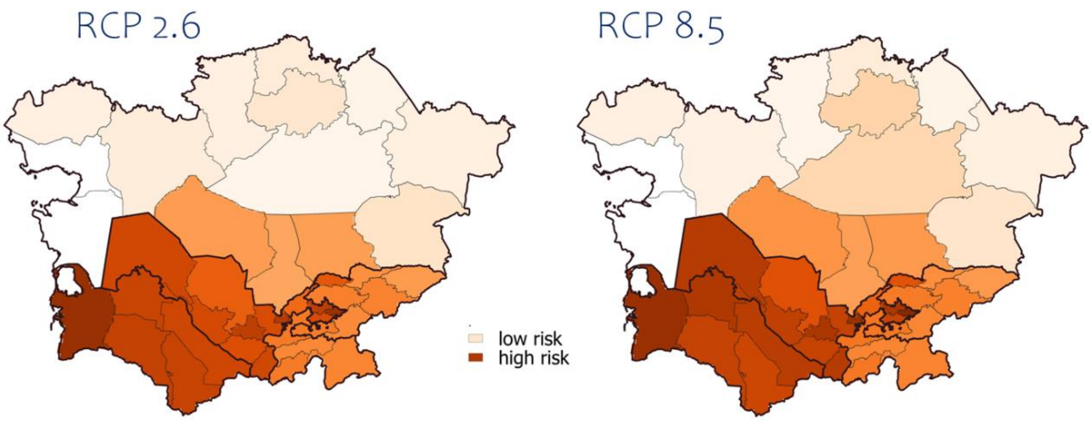


Figure 10. Vulnerability of Central Asian provinces to projected climate-induced stress under the two RCPs

IV. Compound risks for crop production in the region

The vulnerability component of agricultural output in Central Asia was determined using the most recent available yield predictions from the global crop modeling experiments. This comprised the yield projections for wheat, maize, and rice from Jägermeyr et al., 2021 and cotton yield projections from Jans et al., 2021 (see Annex 2). These estimates indicate that wheat yields in Central Asia may increase in the future owing to increased CO_2 concentrations, while maize and rice yield expectations remain largely gloomy (Figure 11). Cotton yields may similarly improve as a result of the CO_2 fertilization effect, albeit with a greater degree of uncertainty owing to the use of a single crop model.

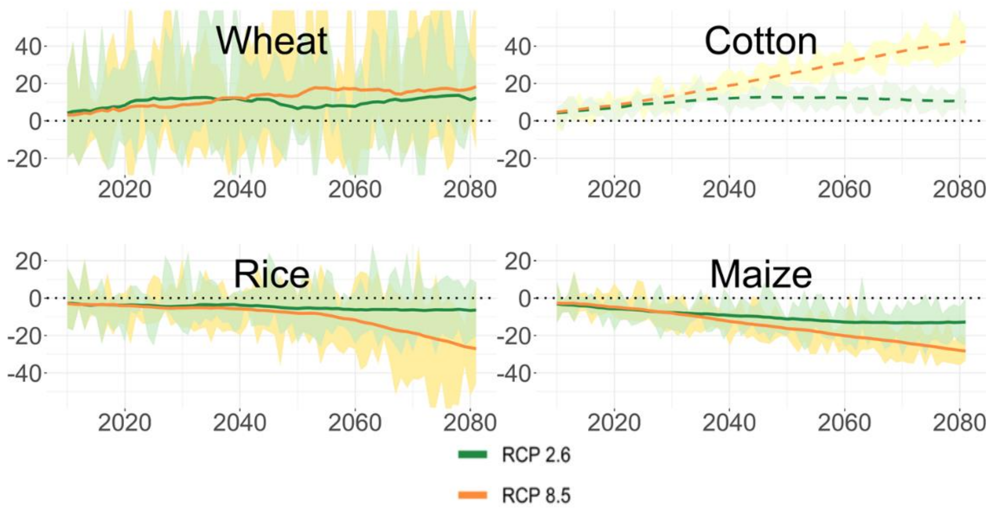
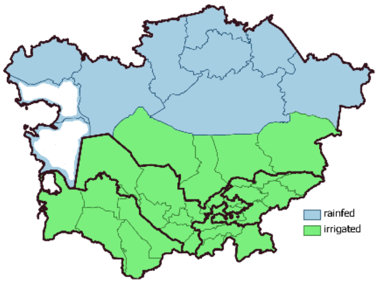


Figure 11. Projected change in crop productivity in Central Asia under RCP 2.6 and RCP 8.5

However, one important feature behind the crop yield projections is that they were determined under the assumption of no water constraints in the future. Crop production in the region can be classified into two distinct water-use zones: most of the northern part of the domain is predominantly devoted to rainfed cereal production, while the arid climate in the southern portion of the territory limits crop production to irrigation (see Figure 12). It is worth emphasizing here that the majority of southern provinces already experience water scarcity; this is far worse in Turkmenistan and Uzbekistan (CAREC, 2021). As illustrated previously, climate change may magnify water scarcity in this part of the domain in the future under both scenarios. Considering the existing crop pattern across the provinces and predicted changes in water availability, future increases in agriculture productivity in the southern provinces may therefore be hampered by growing water scarcity (Figure 13).

Figure 12. Central Asia in terms of rainfed vs irrigated crop production zones



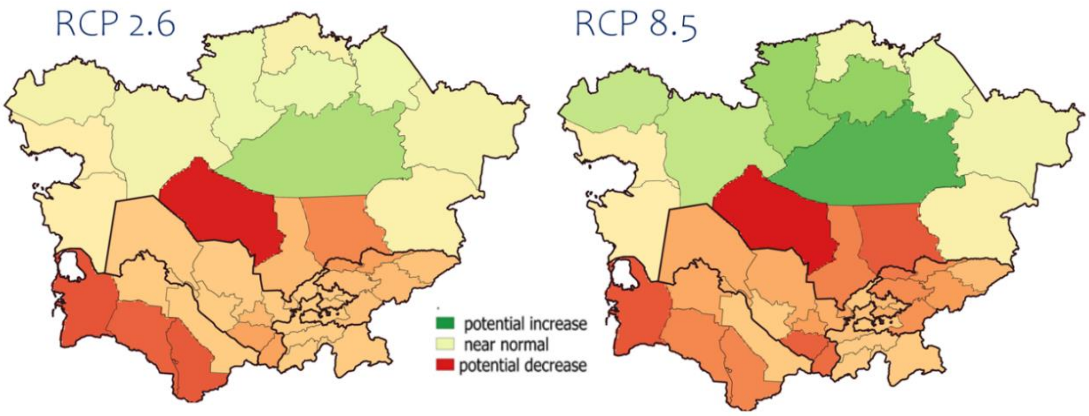


Figure 13. Resulting changes in agriculture productivity at province level by 2040-2069 with respect to 1983-2013, adjusted for projected seasonal water availability and crop structure

While the present crop structure in Central Asia is generally heterogenous, certain provinces in the region place an overwhelming emphasis on growing specific crops. For instance, in 2020 rice accounted for approximately 50 percent of the total cropped area in Kazakhstan's Kyzylorda province. Similarly, cotton accounted for more than 40 percent of the cropped area in Uzbekistan's Syrdaryo, Bukhara, and Khorezm provinces. For the Kyzylorda province, this reliance on monocropping threatens the local agricultural sector on two fronts: a decline in anticipated rice production and increased water scarcity. Despite some benefits of higher growth temperatures and CO_2 fertilization on cotton yields, these potential gains will likely be offset by declining water availability in the majority of the provinces of Uzbekistan and Turkmenistan.

The exposure to expected changes in agricultural productivity by province will be either magnified or nullified by the importance of the agricultural sector to the local economy. At present in some provinces, the sector accommodates more than half of total employment and contributes to 50 percent of the GRP output (Figure 14). The share of agriculture in total employment is notably higher in most provinces of Turkmenistan, except the Balkan province in the west, and the Khatlon province in the south of Tajikistan. In terms of the share of GRP, agriculture stands as an important sector across most provinces in the south of the region, except those that have substantial contributions from mining and fossil fuel extraction industries, such as Balkan in Turkmenistan (natural gas) or Navoi in Uzbekistan (gold mining).

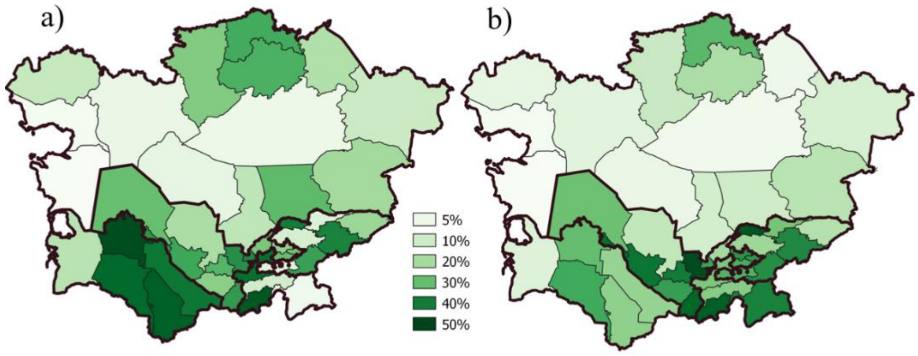


Figure 14. Share of the agricultural sector in a) total employment and b) GRP (excludes fossil fuel extraction and procession industry)

Figure 13 illustrates how the climate vulnerability of agriculture may propagate in the future, given the projected changes in agricultural productivity and the sector's economic importance in each province. This projection assumes that present crop structure and water use efficiency in agriculture remain constant. As a result, the vulnerability hotspots are largely dominated by provinces engaged in irrigated crop production, where seasonal water availability may decrease in the future and where agriculture is a significant employment sector. These provinces with a relative susceptibility to climate change continue to be vulnerable in both climatic scenarios. They include Ahal and Mary (Turkmenistan), Surkhandarya and Kashkadarya (Uzbekistan), Kyzylorda and Dzhambul (Kazakhstan), and Talas (Kyrgyzstan).

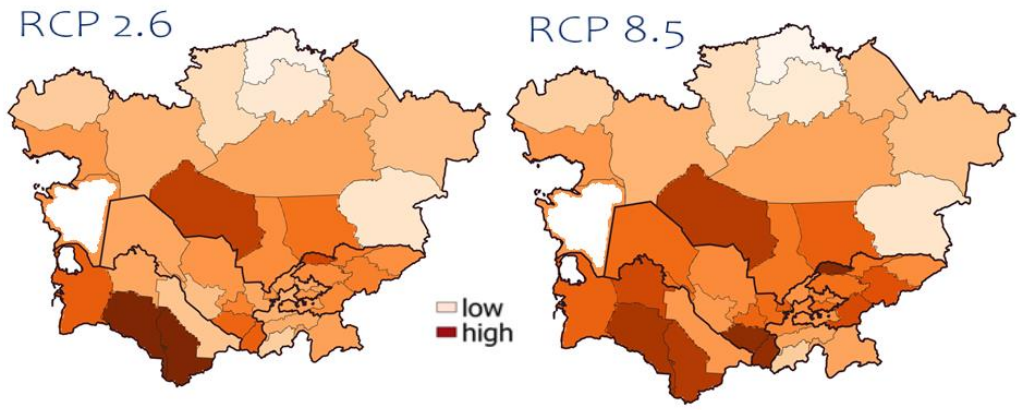


Figure 13. Relative vulnerability of agriculture to climate change at provincial level

V. Multiple challenges for long-term electricity security

The exposure component of the energy vulnerability index combines two issues that Central Asian countries face in ensuring a long-term balance between electricity supply and demand. The former is associated with predicted increases in electricity demand, whereas the latter is associated with the requirement to reduce GHG emissions as part of a country's commitment to the Paris agreement. Owing to continued population expansion and economic development, energy outlooks show that power demand in Central Asian countries by 2050 will likely increase by at least 50 percent from current levels, and possibly by almost 90 percent in Kazakhstan (Figure). On the other hand, the countries' compliance with the global climate agreement requires that any incremental increase in generation capacity should come largely from renewable sources. While all Central Asian countries have made their climate pledges under updated INDCs for 2030, they have also noted that they consider achieving carbon neutrality by 2050-2060. The carbon neutrality target is thus employed as one of the study's underlying assumptions on the primary challenges that the countries must address.

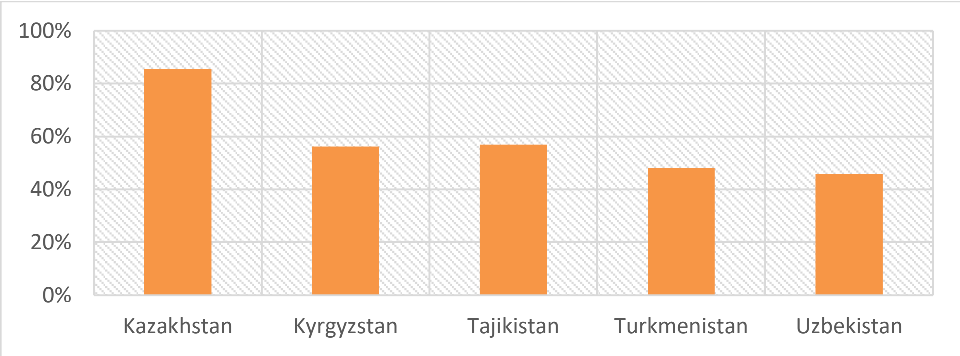


Figure 16. Projected increase in electricity in Central Asia by 2050 with respect to 2020

Source: IEA, 2021b

Achieving long-term electricity generation while reducing the sector's carbon emissions will not be an easy feat for the states. This is especially challenging for Kazakhstan, Turkmenistan, and Uzbekistan, where the electricity industry at present is substantially dependent on fossil fuel combustion (Figure). This stands in stark contrast to Tajikistan and Kyrgyzstan, which rely on hydropower for more than 90 percent of total electricity production and have some of the lowest GHG emissions per kWh produced in the world. Another significant aspect that predisposes the region's sensitivity to possible power demand–supply imbalances in the future is the region's relatively low economic efficiency of electricity use (Figure). In comparison to the European Union, for example, some Central Asian states use multiples of the amount of electricity per GDP, with Tajikistan and Kyrgyzstan having particularly high levels of consumption.

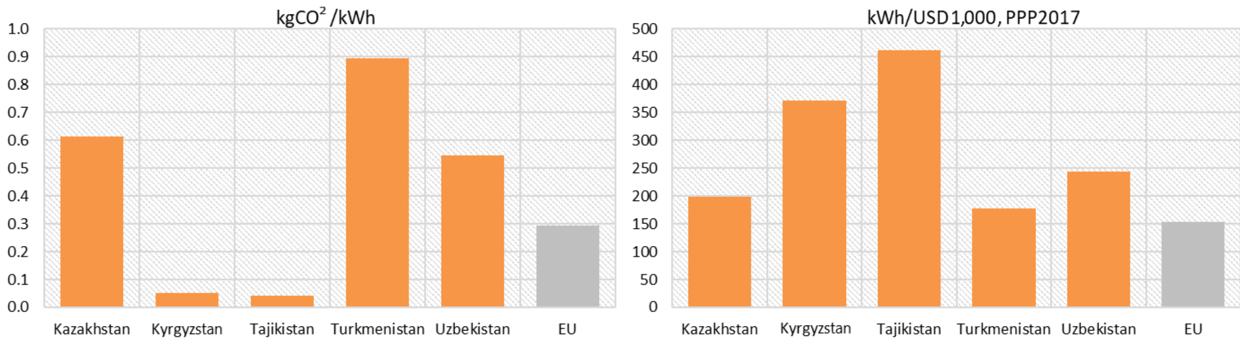


Figure 17. Energy and carbon intensity of Central Asian states
Left: GHG emissions of electricity generation ($kgCO_2$/kWh)
Right: Electricity consumption per GDP (kWh/USD1,000 PPP2017)

The study used gross national income (GNI) per capita as an indicator measuring the state of the development and as one of the main criteria reflecting the adaptive capacity of the Central Asian countries. Besides that, the adaptive capacity was also approximated by using the GE index, which reflects the ability of the states to provide quality public services, to maintain quality civil service, and to design and implement sound policies, as well as the credibility of the government commitment to such policies. Figure 14 illustrates the distribution of the GE index and estimated GNI per capita in the region. With regard to the GNI per capita, there is a large disparity between the countries, with most provinces in Kyrgyzstan and Tajikistan having the lowest levels in the region, followed by Uzbekistan.

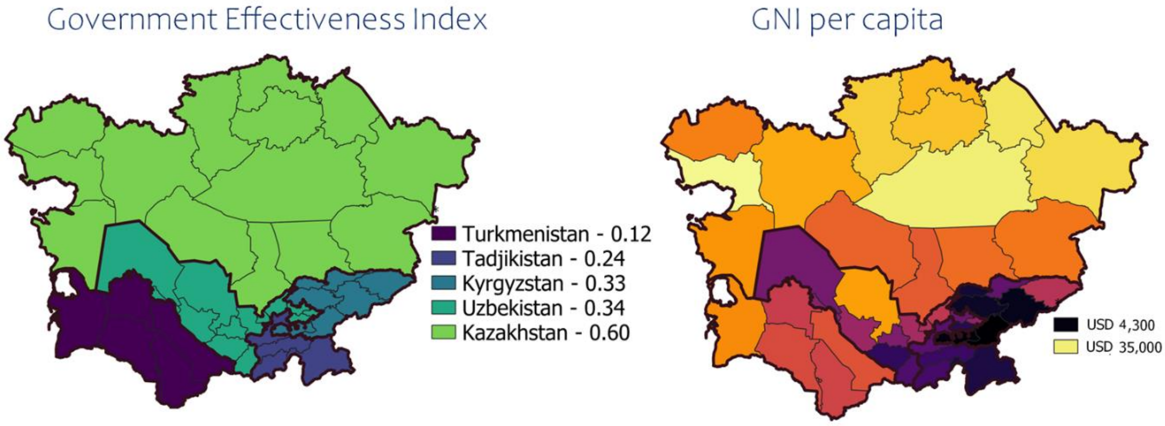


Figure 14. Variables used to characterize adaptive capacity across countries and provinces

Additionally, it is assumed that the countries can improve their energy security by maintaining an adequate structure of their power systems, which can be accomplished by diversifying their supply sources and prioritizing low-carbon generation technologies (IEA, 2020). In this context, the power diversity index was chosen as an extra element for estimating the sector-specific adaptive capacity. It assesses the diversity of primary resources employed in generation. The power diversity index demonstrates that Central Asian countries rely on a narrow spectrum of primary energy sources to meet their needs in electricity. Most of the generation in Turkmenistan and Uzbekistan is based on natural gas thermal power plants. Kazakhstan has a relatively more diverse fuel mix, thanks to the availability of coal, oil-fired, and natural gas power plants. As previously stated, Tajikistan and Kyrgyzstan rely heavily on hydropower for the majority of their electricity, placing them at a slightly lower level in terms of the power diversity index (see Figure 19).

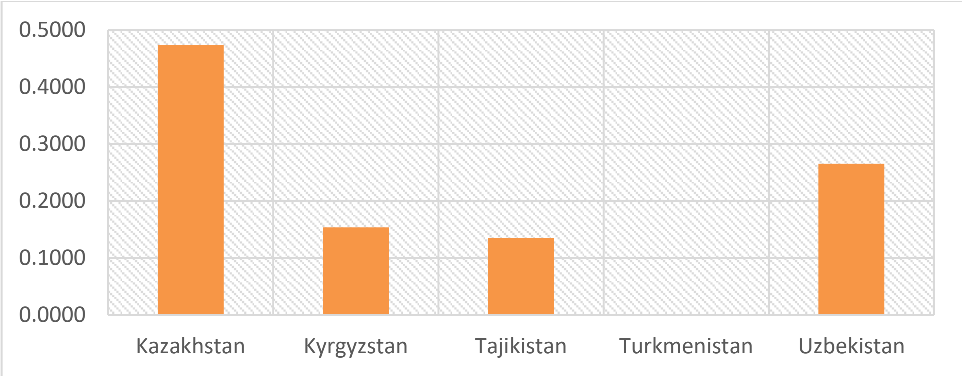


Figure 15. Power diversity index of Central Asian countries

Figure estimates the total susceptibility of Central Asian countries by contrasting issues connected with long-term electricity demand and global climate mitigation imperatives, their current energy and carbon intensities, as well as their governance and economic performance.

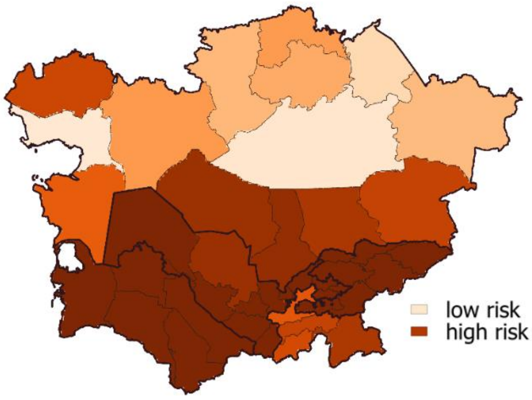


Figure 20. Vulnerability to risks associated with maintaining electricity supply–demand balance and reaching carbon neutrality

VI. Accounting for the role of regional cooperation

As indicated in the introduction, the region's water resource utilization is highly transboundary, placing considerable reliance on countries located downstream of the respective river basins for the timely release of water from large hydroelectric dams upstream. These transboundary links are especially strong in the south of the region, where the majority of river runoff originates in the highlands of Tajikistan and Kyrgyzstan, while the bulk of river withdrawals occur in Uzbekistan, Turkmenistan, and southern Kazakhstan. The reliance on water resources across the upstream and downstream states in the region has contrasting patterns. Owing to the absence of fossil fuel reserves, for upstream states water is the primary resource for electricity. On the other hand, water is a critical resource for crop production in downstream countries, which is only possible here through irrigation. The seasonal cycles of these two needs do not coincide (Figure 21), implying a substantial need for regional collaboration in Central Asia's water–agriculture–energy nexus.

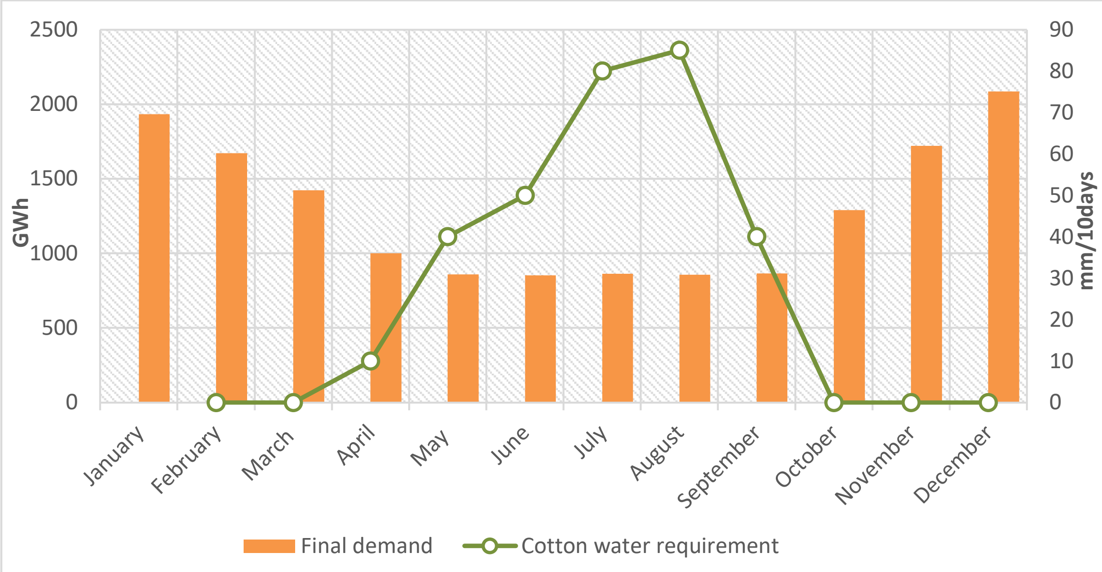


Figure 21. Case of Syr Darya basin: seasonal patterns of electricity demand upstream (Kyrgyzstan) versus cotton water requirements downstream (Ferghana Valley)

Source: adapted from KESC, 2021 (electricity demand); Conrad et al., 2013 (cotton crop water requirement)

According to the underlying assumptions of the study, a strong reliance on inflowing water resources contributes to the sensitivity of the downstream states to changes in water discharge owing to climate change. However, with sufficient cooperation among governments on integrated water resource management, transboundary water dependency may become a much more negligible component. Figure 22 illustrates how vulnerability hotspots alter when the water dependency indicator is omitted from the experimental settings of the study.

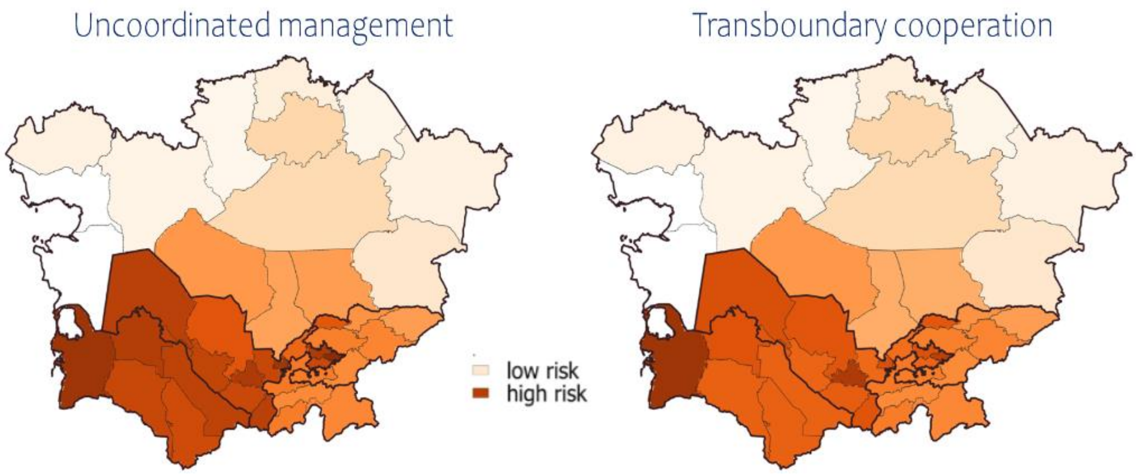


Figure 16. The magnitude of climate-induced water stress threats under two cooperative performance scenarios

Because crop production in this water-stressed region is highly dependent on timely water releases from upstream systems, the agricultural sector also benefits from greater transboundary cooperation. The reduced magnitude of water availability risks, in particular, may partially alleviate constraints on agricultural productivity in impacted provinces. This is especially relevant for wheat and cotton, which (as previously shown) may have the potential for higher yields in this part of Central Asia based upon increased CO_2 fertilization and an adequate supply of irrigation water. For crops that have negative prospects under increasing temperatures—such as rice, maize, and soybeans—water cooperation could help to avoid the additional risks associated with water irrigation deficits.

Cooperative management over the transboundary water resources in the region entails stronger collaboration on electricity exchanges between the countries. Figure 23 illustrates disparities between electricity demand and supply in Tajikistan on a monthly scale when its hydroelectric facilities operate in a manner that benefits timely water availability for the downstream states. Joint water resource management thus implies that the upstream countries have more flexible possibilities to offset seasonal shortages and surpluses through transboundary electricity trade. Thus, cooperative water resource management presupposes that the upstream countries have the ability to compensate for their seasonal electricity shortages and surpluses via transboundary electricity exchange.

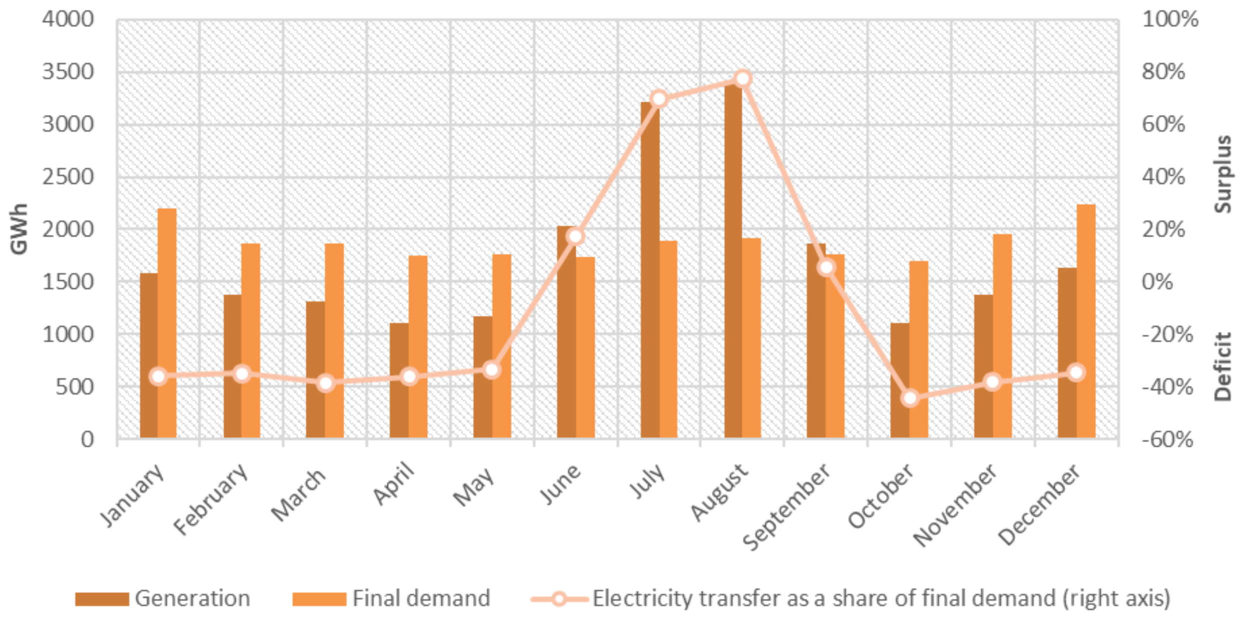


Figure 17. Monthly electricity balance in Tajikistan

Source: based on IEA, 2021a

However, the overall benefits of regional cooperation are far greater than simply offsetting seasonal imbalances in power supply and demand, since it also results in lower power generation costs and avoids capital expenses for redundant power capacity, as well as giving better options for GHG emission reductions and favorable conditions for the use of intermittent renewable energy sources (World Bank, 2017; Shadrina, 2019). Additionally, it contributes to a higher diversity of power supplies and the primary energy sources upon which they are based (Figure 18), which is another important component of the energy security concept.

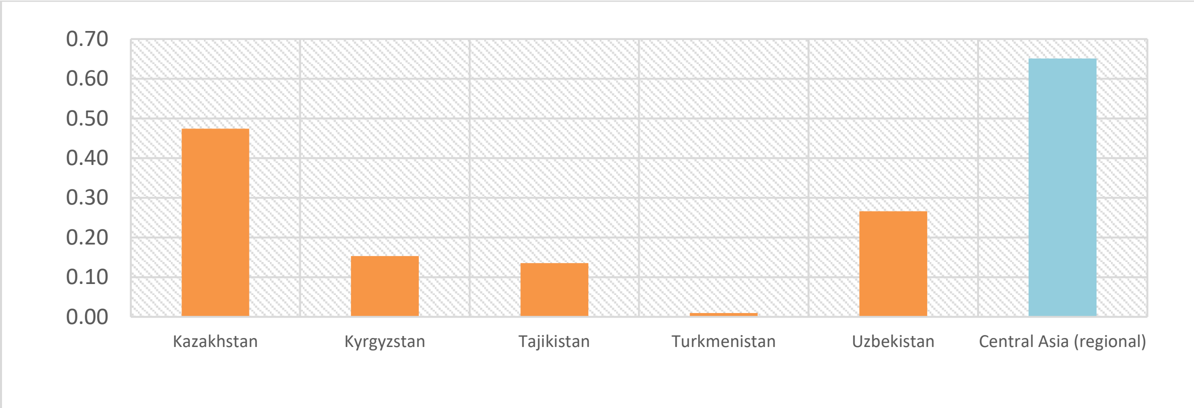


Figure 18. Power diversity index in Central Asia on a country versus regional level

VII. Conclusions

This study examines the climate vulnerabilities of the water, agriculture, and energy sectors in the Central Asian provinces. Using an index-based approach, the study quantifies and juxtaposes major climate risks, corresponding socioeconomic sensitivities, and adaptive capacities for the water resources and agriculture sectors in the provinces. For the energy sector, the study examines long-term electricity security in light of rising demand and the compelling need to reduce associated GHG emissions.

The findings suggest that climate change will likely alter water resources in Central Asia with contrasting trends across the provinces in the region. Although subject to relatively higher uncertainty on an annual scale, the projections used in this study indicate that river discharge may decrease in the river basins that are a part of the larger Aral Sea basin in the south of the region, whereas river discharge may increase in the north. The shifts in river flows may be more pronounced in the future under both climate scenarios during the vegetation season, when water is most needed for irrigation in the southern part. Given that most rivers in the region are subject to high interannual runoff variation, improving the early warning systems to existing variability is a good initial and win-win step towards achieving long-term resilience.

Excessively high dependence on water resources is among the main reasons for high susceptibility across Central Asia to climate change impacts. This dependence is also rooted in low economic productivity of water use, especially in the southern provinces. Most provinces in Turkmenistan, Uzbekistan, and southern Kazakhstan already suffer from high levels of water stress; therefore, any further gap between water availability and demand would have excarnating implications for water-intensive sectors. The countries should prioritize increasing water use efficiency across the sectors as a means of reducing their sensitivity to the adverse impacts of climate change. This is especially true for agriculture, which is by far the largest water consumer. Given the current high level of economic reliance on water resources, promoting alternative, less water-intensive sectors of the economy could be a promising additional adaptation approach. Apart from being a general requirement in the development context, this imperative would also strengthen the structural resilience of local economies to anticipated water stress.

Projected shifts in water availability may therefore have a far-reaching consequence for other sectors, with agriculture being the major recipient of the transferred water-related risks. Climate change will likely have heterogenous impacts on the production of major crops grown in the region. Yield projections from the recent global crop modeling experiments suggest that maize, rice, and soybeans will likely see a decrease in productivity, while wheat and cotton crops may potentially benefit from the rising temperatures and higher carbon fertilization. Even so, the potential benefits for cotton and wheat would largely vanish in the southern part of the region: crop productivity here will be deteriorated by the projected decline in water for irrigation. Reducing reliance on monocropping and crop structure optimization could diminish the sensitivity of the local agricultural sector to climate change; it needs to be complemented with careful selection and aligning of crop varieties to the changing local climate conditions. The drought-resistance of crop cultivars will likely become one of the important criteria in cropping decisions.

As a result, most provinces in the southern half of the region may see a decline in agricultural productivity. This would be exacerbated in certain provinces by excessive monocropping, when agriculture is dominated by one or a few crops that have either negative prospects under climate change or are water-intensive. These impacts will be magnified by the relatively higher importance of agriculture in those provinces, in terms of the share of the population engaged and the contribution of the sector to regional GDP. In this regard, the diversification of local economies and consequent decline in the sector's relative socioeconomic importance may become one of the few viable adaptation strategies in such provinces.

All Central Asian countries face a common challenge of maintaining a long-term balance of power demand and supply, given that power consumption is expected to grow by more than half of present generation levels. The global climate agreement places an additional burden of carbon reduction—particularly on Kazakhstan, Turkmenistan, and Uzbekistan, where electricity generation is significantly more carbon-intensive. This race for power security is compounded in most countries by a high energy intensity of GDP. While the southern areas of the region are more sensitive to long-term mismatches in power supply–demand, the findings show that many provinces in Kazakhstan are equally vulnerable. Improving energy efficiency appears to be an important and cost-effective step. Many provinces in the region should also prioritize the development of less energy-hungry economic sectors. Nonetheless, although costly, the large-scale adoption of renewable energy sources is unavoidable.

The study uses GNI per capita and the GE index as proxies for adaptation capacity across the Central Asian countries and provinces. As a country's vulnerability to climate change is proportional to its economic development, developing countries are generally more sensitive to negative climate change impacts than industrialized countries. Owing to the high costs associated with both the impacts of climate change and adaptation to these impacts, lower-income provinces in the region will bear a disproportionate share of the economic burden. In addition, an appropriate institutional framework enables the preparation for and adaptation to climate change. The capacity of countries to deliver public services and establish and implement sound policies is viewed as a necessary element for improved development outcomes. All Central Asian countries, on the other hand, are characterized by relatively weaker government effectiveness, which may impede adaptation attempts.

Given that many provinces in Central Asia's adaptation capacity are confined by their relatively low economic performance, international development finance will be necessary to strengthen their climate resilience in the face of climate threats. However, mobilizing resources alone is unlikely to be sufficient for adaptation success. Both central and local governments should continue to build their capacity for designing and executing effective policies.

The transboundary nature of the distribution of water resources across Central Asia predisposes that the countries have a high degree of interdependence and sensitivity to compound risks when climate-related impacts on water resources transfer to the agriculture sector. Transboundary ties are particularly strong in the south of the region, where the bulk of river runoff originates in the highlands of Tajikistan and Kyrgyzstan, while most withdrawals occur in the irrigated crop production of the downstream provinces. While regional collaboration on transboundary water management alleviates current uncertainties about water supply for downstream provinces, it also minimizes sensitivities and strengthens the adaptation capability of countries to long-term changes in river flow.

The long-term electricity security of the countries can also benefit substantially from the multiple advantages emerging from regional cooperation, in terms of the lower economic cost of electricity and greater flexibility to curb GHG emissions. As exemplified, cooperation improves the diversity of power supplies on a regional scale, which is another important element of energy security. In addition, it could establish favorable conditions for exploiting the yet untapped potential of renewable sources in the region, including the great potential for hydropower in the south.

Annex 1. Methodology (expanded description)

This assessment used an index-based approach, to estimate vulnerability as a function of potential impacts, measured by exposure and sensitivity, and a system's adaptive capacity to withstand anticipated impacts:

Vulnerability index = (exposure*sensitivity)/(adaptive capacity)*, where:*

The **exposure component** quantifies the sector's key challenges associated with climate change. For example, the water sector evaluation focuses on climate-induced water stress, with the long-term predicted water supply serving as the primary indication of projected change. Agriculture's vulnerability score considers projected changes in yield of primary crops farmed in the region (wheat, cotton, maize, oil crops, and rice). The energy sector assessment encompasses challenges to meet a projected increase in power electricity demand, given the climate implications for the water and agriculture sectors as well as the stated carbon reduction targets of the Central Asian countries.

The **sensitivity component** determines the degree to which a system is affected by climate-related implications. To what extent expected variations in wheat yields influence a country or a province depends on whether grain production accounts for a sizable portion of a province's economic activity. This can be quantified in terms of the contribution of wheat farming to regional domestic product and the proportion of the population engaged in agriculture, which we consider here as *reliance* indicators. In turn, *dependency* indicators represent the extent to which a country/province is dependent on external systems for a certain resource. For instance, most of the water resources accessible to the downstream states originate in upstream countries, which may be quantified and factored into the vulnerability assessment using the water dependency ratio. Similarly, intensity indicators quantify the degree to which a resource is integrated into a country's/key province's economic activity. As an example, energy consumption per capita or per unit of GRP serves as a proxy for sensitivity to disruptions in the power demand–supply balance. On the other hand, overall improvements in energy efficiency reduce the sensitivity to projected changes in energy supply.

The **adaptive capacity** refers to ability to adapt to the expected climate implications. For all three sectors, the study universally uses the same indicators that measure economic, institutional, and human capacity to absorb adverse effects and/or capitalize on any favorable prospects. The economic capacity is represented by GNI per capita as an indicator measuring the state of development and as one of the main criteria reflecting adaptive capacity of the Central Asian countries. Institutional and human capacity is approximated by using the GE index, which reflects state ability to provide quality public services, to maintain quality civil service, to design and implement sound policies, and the credibility of government commitment to such policies.

The following four steps illustrate the approach for estimation of vulnerability, using as an example the agriculture sector in Namangan province in Uzbekistan and the projections under the RCP 8.5 scenario:

Step 1: Estimation of the province level exposure:

- Estimate relative change in productivity of the four crops for spatial domain of target province from the global crop projections
- Using actual crop structure in the province determine the coefficient of change in province-aggregated agriculture productivity
- If a targeted province is irrigated, combine the coefficient of projected agricultural productivity with coefficient that reflects projected change in seasonal discharge

  - *Projected change in seasonal discharge for the Namangan province = -19 percent*
  - *Projected change in agriculture productivity for the Namangan province = +16 percent (two-thirds of the total crop area in Namangan are under wheat and cotton)*

$$\text{Climate exposure for the agricultural sector in Namangan province} = \underbrace{1.16}_{\textit{coefficient of projected change in agricultural productivity}} + \underbrace{(-1.19)}_{\textit{coefficient of projected change in seasonal water availability}} = -0.3$$

Step 2: Determination of the province level sensitivity and calculation of the potential impact:

- Estimate share of agriculture in GRP and in total employment in a target province
- If the province is in the downstream and crop production is irrigated, sensitivity indicators also include water dependency ratio
- Sensitivity is determined by averaging the sensitivity indicators

$$\text{Sensitivity for the agricultural sector in Namangan province} = (\underbrace{0.24}_{\textit{share of agriculture in total employment}} + \underbrace{0.37}_{\textit{share of agriculture in GRP}}) / 2 = 0.31$$

- Overall potential impact is a product of exposure and sensitivity coefficients

$$\text{Potential impact for the agricultural sector of the Namangan province} = \underbrace{-0.3}_{\textit{Exposure}} * \underbrace{0.31}_{\textit{Sensitivity}} = -0.06$$

Step 3: Estimation of the adaptive capacity:

- Adaptive capacity is determined by averaging a country's GE index and estimated GNI per capita in the province (normalized between 0 to 1 using max and min values across all provinces)

$$\text{Adaptive capacity coefficient for Namangan province} = (\underbrace{0.06}_{\textit{Quantile of the GNI per capita (benchmarking with respect to all provinces in Central Asia)}} + \underbrace{0.34}_{\textit{GE Index of the country (percentile ranking)}}) / 2 = 0.2$$

Step 4: Calculation of the vulnerability index

The vulnerability index is calculated by juxtaposing the resultant score of potential impacts with the adaptive capacity score:

$$\text{Vulnerability index for the agriculture sector in Namangan province} = \underbrace{-0.06}_{\textit{Potential impact score}} / \underbrace{0.2}_{\textit{Adaptive capacity score}} = -0.3$$

Annex 2. Estimation of future climate risks for the water and agriculture sectors

1. Projected change in river discharge

The study used simulation output from the three global hydrological models participating in the Intersectoral Impact Model Intercomparison Project, phase 2b (ISIMIP, 2022): WaterGAP 2.2c (Müller Schmied et al., 2016); MATSIRO (Takata, Emori, and Watanabe, 2003); and H08 (Hanasaki et al., 2018), which were forced by three global climate projections: HadGEM2-ES, IPSL-CM5A-LR, and GFDL-ESM2M models (Frieler et al., 2017).

Discharge projections under RCP 2.6 and RCP 8.5 were extracted and averaged to annual time steps for the rivers represented in Figure 1 (see Report). Seasonal discharge projections were estimated by averaging the projections for the months of April through to September. To estimate future change in river discharge, the study averaged discharge over 2040-2069 under the two climate scenarios and compared with the average at the baseline period of 1975-2005.

Table A1. Evaluation of three hydrological models (forced with WATCH and EWEMBI) using annual discharge data for Amudarya and Syr Darya rivers (1971-1991)

Hydrological model	Amudarya river, Kerki station		Syr Darya river, Naryn-Toktogul station	
	R^2	KGE	R^2	KGE
H08	0.59	0.55	0.43	0.24
MATSIRO	0.53	0.25	0.7	0.19
WaterGAP2c	0.67	0.53	0.43	0.25

2. Projected change in crop productivity

To estimate changes in agriculture productivity of wheat, maize, and rice across Central Asia, the study employed crop yield projections generated by ensembles of latest-generation crop and climate models (Jägermeyr et al., 2021) that are a part of the Agricultural Model Intercomparison and Improvement Project (AgMIP, 2022). In addition to these crops, the study used projections for cotton yields that come from another research experiment (Jans et al., 2021), based on a single crop model. The relative changes in crop productivity under RCP 2.6 and RCP 8.5 in these projections were estimated as the difference between mean yield over 2040-2069 and mean yield over 1983-2013 (baseline).

The crop projections were adjusted for observed crop frequency across Central Asia using estimates from the global gridded crop harvested area (Grogan et al., 2022). To estimate the overall projected change in agricultural productivity at province level, the crop projections were averaged taking into account the present cropland structure in each province (see Annex 3 for data sources on province crop structure).

Annex 3. Data sources for the main indicators

	Indicators	Aggregation level	Kazakhstan	Kyrgyzstan	Tajikistan	Turkmenistan	Uzbekistan
Water sector indicators	Projected change in water availability under RCP 2.6/RCP 8.5	Province	Hydrological projections of discharge from ISIMIP, phase 2b (see Annex 2 for details)				
	Water withdrawal to availability ratio	Province	AQUASTAT database (FAO, 2022)				
	Water consumption per Gross Regional Product (GRP). GRP estimates were adjusted by excluding fossil fuel extraction and processing industries.	Province	Water withdrawals estimated from WaterGAP2c hydrological model (see Annex 2), estimation of province level GRP used the same data sources as for indicator 'Share of agriculture in GRP' below				
	Water dependency ratio	Country	AQUASTAT database (FAO, 2022)				
Agriculture sector indicators	Projected change in yields of wheat, maize, rice, and cotton under RCP 2.6/RCP 8.5	Province	Crop yield projections from Jägermeyr et al., 2021 and Jans et al., 2021 (see Annex 2)				
	Projected change in water availability (applied only for provinces with irrigated crop production)	Province	Hydrological projections of discharge from ISIMIP, phase 2b (see Annex 2)				
	Crop-specific area as a fraction of total harvested area	Province	(StatdataKZ, 2021)	(StatdataKG, 2022a)	(StatdataTJ, 2017)	(StatdataTM, 2018)	(Djanibekov and Petrick, 2020)
	Share of agriculture in GRP. GRP estimates were adjusted by excluding fossil fuel extraction and processing industries.	Province	(StatdataKZ, 2021)	(StatdataKG, 2022c)	(Hoshimov, 2017)	(Corradini and Dergunova, 2012)	(StatdataUZ, 2020)

	Share of population engaged in agriculture	Province	(StatdataKZ, 2021)	(StatdataKG, 2022b)	(StatdataTJ, 2017)	(Corradini and Dergunova, 2012)	(StatdataUZ, 2020)
Energy sector indicators	Projected increase in power demand by 2050	Country	(IEA, 2021c)				
	GHG mitigation	Country	Assuming transition to carbon neutrality in 2050-2060 as a goal				
	Electricity consumption per GRP	Province	(IEA, 2022)				
	Carbon intensity of power generation	Country	(IEA, 2019)				
	Electricity diversity index	Country	(IEA, 2022)				
Adaptive Capacity Indicators	Government effectiveness	Country	(World Bank, 2022)				
	GNI per capita	Province	(statdataKZ, 2021; World Bank, 2022)	(StatdataKG, 2021; World Bank, 2022)	(Hoshimov, 2017; World Bank, 2022)	(Corradini and Dergunova, 2012; World Bank, 2022)	(World Bank, 2022)

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CARECT INSTITUTE

Central Aisa Regional Economic Cooperation (CAREC) Institute
No. 376 Nanchang Road, Sha Yi Ba Ke District, Urumqi, 830000
Xinjiang Uygur Autonomous Region, the People's Republic of China
f: +86.991.8891151 | www.carecinstitute.org
km@carecinstitute.org | www.carecinstitute.org