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NARRATIVE REPORT

Developing an Integrated Water-Food-Energy-Ecosystem model for the Amu Darya basin (with application of WEAP and LEAP modeling software)

Forward

The results presented in this report are based on a large multi-year collaboration across the 5 countries of Central Asia, including government representatives, members of civil society, research organizations and non-government organizations.

Of particular note are the contributions of local national experts, including:

- Kazakhstan: Aliya Nurbatsina (Institute of Geography and Water Security JSC)
- Kyrgyz Republic: Elvira Omorova (Hydromet) and Olga Kalashnikova (Central Asian Institute of Applied Geosciences)
- Tajikistan: Jafar Niyazov (Institute of Water Problems, Hydropower and Ecology of the Academy of Sciences)
- Turkmenistan: Arif Mammadov (National Automation Expert)
- Uzbekistan: Andrey Petrov (SRI IVP) Denis Sorokin (SIC ICWC)

INTRODUCTION

The USAID Central Asia’ Regional Water and Vulnerable Environment Activity (hereafter, the Activity) is a five-year project that aims to strengthen water cooperation among Central Asian countries to increase stability, economic prosperity, and healthy ecosystems. The Activity is implemented by a Tetra Tech ARD Inc. branch in the Republic of Kazakhstan.

One of the objectives of the Activity is to facilitate and promote the Robust Decision Support (RDS) process among stakeholders at the level of the Syr Darya and Amu Darya River basins, which will support strategic planning and decision-making towards sustainable development of the region. The RDS process is accompanied by the development of an integrated water-energy-food-ecosystems (WEFE) and macroeconomic models for these basins and associated countries.

The modeling approach is to combine a water planning model, built with the Water Evaluation and Planning (WEAP) modeling platform, with an energy planning model, built with Low Emissions Analysis Platform (LEAP) and Next Energy Modeling system for Optimization (NEMO), and a macroeconomic model, Macro, which is designed to work with LEAP. The LEAP/NEMO, WEAP, and Macro models are run iteratively to convergence (see Figure 1).

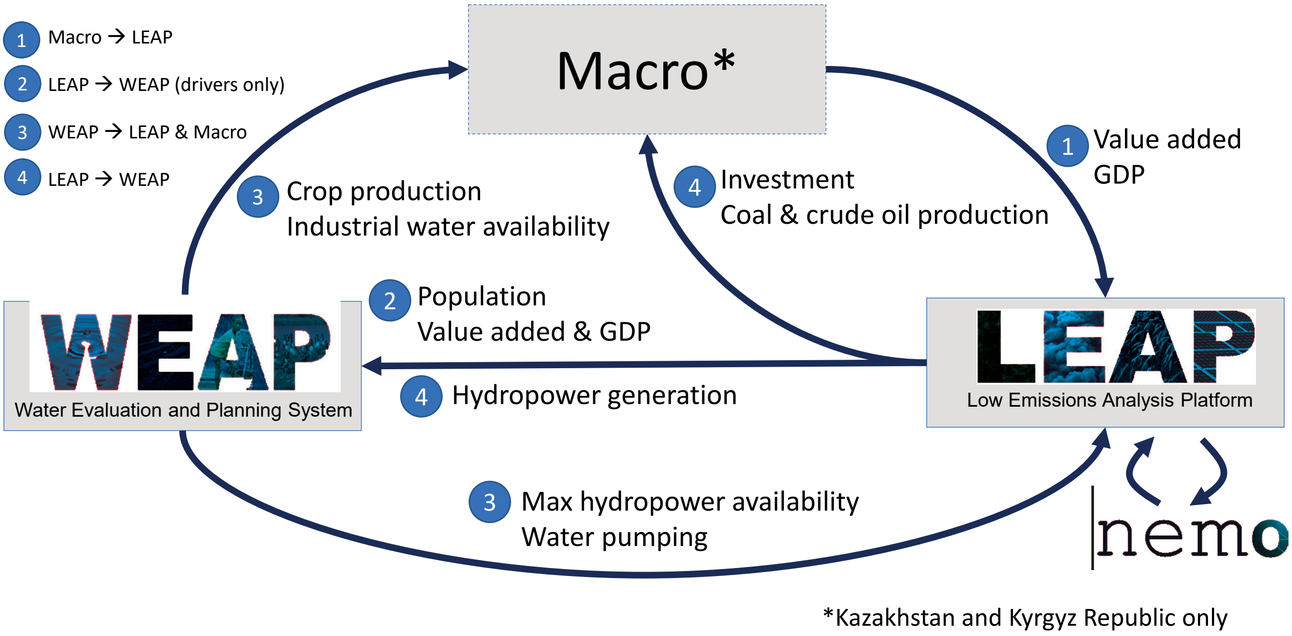

Figure 1. illustration of the interlinkages between LEAP, WEAP, and Macro: Models are run to convergence.

The Stockholm Environment Institute in the USA (SEI) is the developer of these models and the main partner of the Activity to implement this task.

This report focuses on the results achieved for the Amu Darya River Basin modeling. The Syr Darya has been previously presented and can be found at https://www.riverbp.net/upload/iblock/2b4/dqjexjnzueqxo14rnh3pbvpxd9y3m1nh.pdf

NOTE: All the data used for the modeling is publicly open data from national agencies and international datasets. Scenarios were developed in consultation with national partners of the basin countries and may differ from current country/industry development trends. Numbers in modeling results may differ from the actual situation in the countries, but these results reflect development trends. The development of an integrated water-energy model by means of WEAP and LEAP modeling tools was carried out to demonstrate the benefits of using such tools in its integration to improve long-term and integrated planning.

ROBUST DECISION SUPPORT PROCESS

The Amu Darya basin and its associated countries – Kyrgyz Republic, Tajikistan, Uzbekistan and Turkmenistan – are facing deep uncertainties going into the future. Key among these are potential different climate projections and the new construction developments, including the Qosh Tepa irrigation canal in Afghanistan. The Robust Decision Support (RDS) process is a method of planning that identifies more robust pathways in the face of deep uncertainty, unlike more traditional approaches that assume the future is more predictable.

In the case of the Amu Darya, the interconnectedness of water, energy and agriculture requires an integrated approach. If these sectors are treated separately important tradeoffs and synergies will be missed. The Activity used a WEFE approach in combination with RDS.

Furthermore, the RDS process explicitly engages stakeholders to ensure that decisions have buy-in and trust among the participants. The Activity therefore started with a process of identifying key stakeholders, as shown in Figure 2 below. The stakeholders define the key issues that need to be addressed, and based on that models are developed to be able to identify possible solutions.

Unique to this Activity, the analysis was developed together with a core group of 7 representatives of scientific research institutes in Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan, with 1 to 2 people from each country. This allowed for more in-depth capacity development within Central Asia.

National workshops were held, led by this core team, to identify critical uncertainties, planning and policy options, scenario pathways, and measures of success.

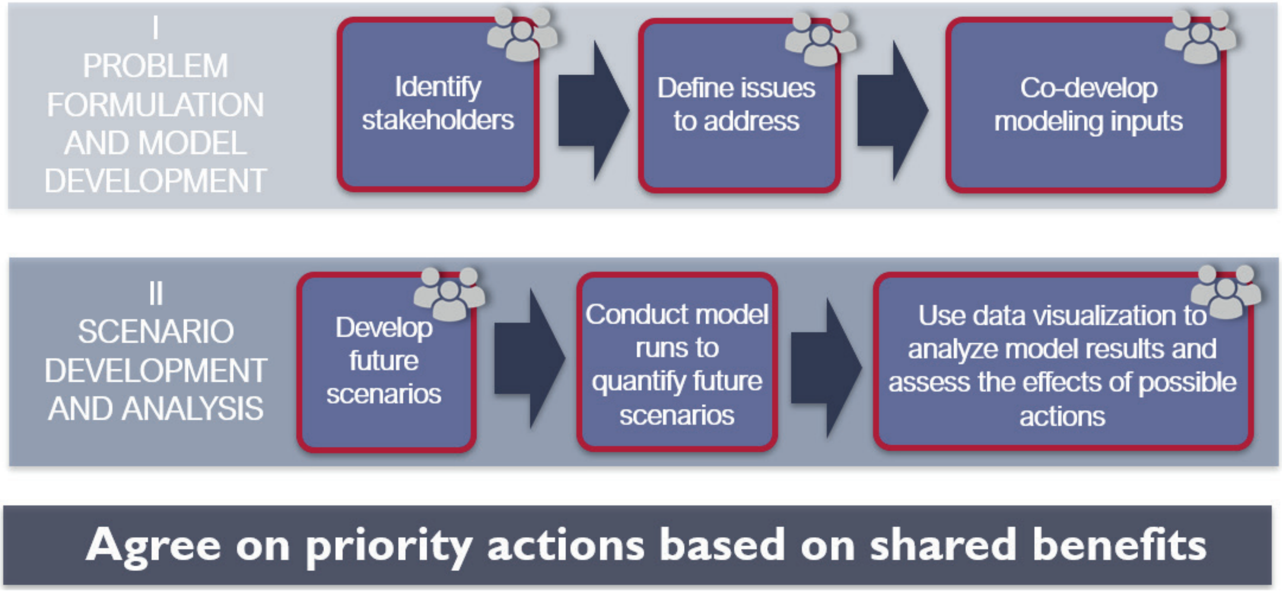

Figure 2. RDS Process

Following on these workshops, the inputs were incorporated into WEAP and LEAP, along with climate projections and scenario narratives to generated alternative pathways that could lead to more or less robust futures. This will contribute to a cross-sectoral understanding of the rational solutions that need to be taken to improve water, energy, food and environmental security in the region within the countries and regionally and, most important for the Activity – to understanding and recognition of benefits of using such a complex approach for better, well-informed and complex decision-making.

Following on the national workshops, the RDS was implemented through regional dialogue between the WEFE sectoral ministries – water, energy, environment, and agriculture, as well as ministries of foreign affairs, research and strategic institutions from all four Amu Darya basin countries – Turkmenistan, Kyrgyz Republic, Tajikistan and Uzbekistan, including also Kazakhstan – as an observer to the process.

MODELING TOOLS

The RDS analysis for the Amu Darya Basin was conducted with a modeling toolkit using publicly available data only, and comprising several interlinked models: a Water Evaluation and Planning system (WEAP) model of the Basin's water resources, a Low Emissions Analysis Platform (LEAP) model of Central Asia's energy systems, and Macroeconomic (Macro) models of national economies. This section provides an introduction to these component models, including their software platforms, structure, inputs, and outputs. Section 3 describes how the models were connected to analyze linkages between water, energy, and the economy.

WATER EVALUATION AND PLANNING (WEAP)

The Water Evaluation and Planning (WEAP) model is a sophisticated water allocation tool designed to assess the performance of water systems under various uncertain factors and management scenarios. Developed by the Stockholm Environment Institute, WEAP is intended to help policymakers, planners, and managers make informed decisions about water resources. The model is particularly useful for evaluating how water systems respond to climate projections, population growth, economic development, and different water management policies or interventions like the construction of new infrastructure.

WEAP Scope and Structure for Amu Darya

Resource management in the Amu Darya river basin is a complex challenge that falls within the nexus of managing competing objectives for water, food, and energy. The basin's water resources are heavily used for irrigating vast agricultural lands, which are essential for food security in the region. Simultaneously, water is required for hydropower generation, which is one of the key energy sources for the countries within the basin and continue to grow with construction of new hydropower plants. Balancing these demands while ensuring sustainable water use and addressing environmental concerns presents a significant management challenge.

The WEAP model was used to develop a water assessment tool for the Amu Darya river basin to evaluate and manage these competing objectives. By simulating various scenarios, the model helps stakeholders understand the implications of different water management strategies. For instance, the WEAP model can simulate the impact of new irrigation projects, changes in crop patterns, or the construction of new hydropower dams on water availability and distribution. It also assesses how climate projections might alter precipitation patterns, snowmelt, and overall water supply in the basin.

Through this comprehensive approach, the WEAP model aids in identifying strategies that balance water use for all sectors important for the economy, including such significant sectors as agriculture and energy production while minimizing negative environmental impacts. It provides a platform for stakeholders to explore trade-offs and synergies between different water uses, ultimately supporting more informed and sustainable water management decisions in the Amu Darya river basin.

Spatial Disaggregation of Water Supplies and Demands

Spatial disaggregation in WEAP is crucial for accurately representing the complex and varied interactions between water supplies and demands across different regions. By dividing a basin into smaller sub-watersheds, the tool can capture localized climate variations, infrastructure, and water use patterns. This detailed spatial resolution allows for more precise modeling of hydrological processes such as snow and glacier melt, rainfall runoff, and irrigation needs. Consequently, it enhances the tool's ability to simulate the impacts of different water management strategies, helping stakeholders make informed decisions that balance competing demands for water, food, and energy while ensuring sustainable resource management.

To effectively capture the distribution of water supplies and demands throughout the Amu Darya basin, the WEAP model was spatially disaggregated into 26 sub-catchments, with the boundaries determined based on the main tributaries and the location of key infrastructure such as dams and canals (Figure 3). This level of subdivision ensures that the model can accurately reflect the hydrological and infrastructural dynamics across different parts of the basin.

The full WEAP model link is provided here: https://www.dropbox.com/scl/fi/mknb9nvmk5jikwsnb776k/WAVE-Amu_Syr_Darya-2023_12_01_integrated-rund_2024-01-06.WEAP?rlkey=ww6hm7xqtrp4c22op79ez65le&dl=0

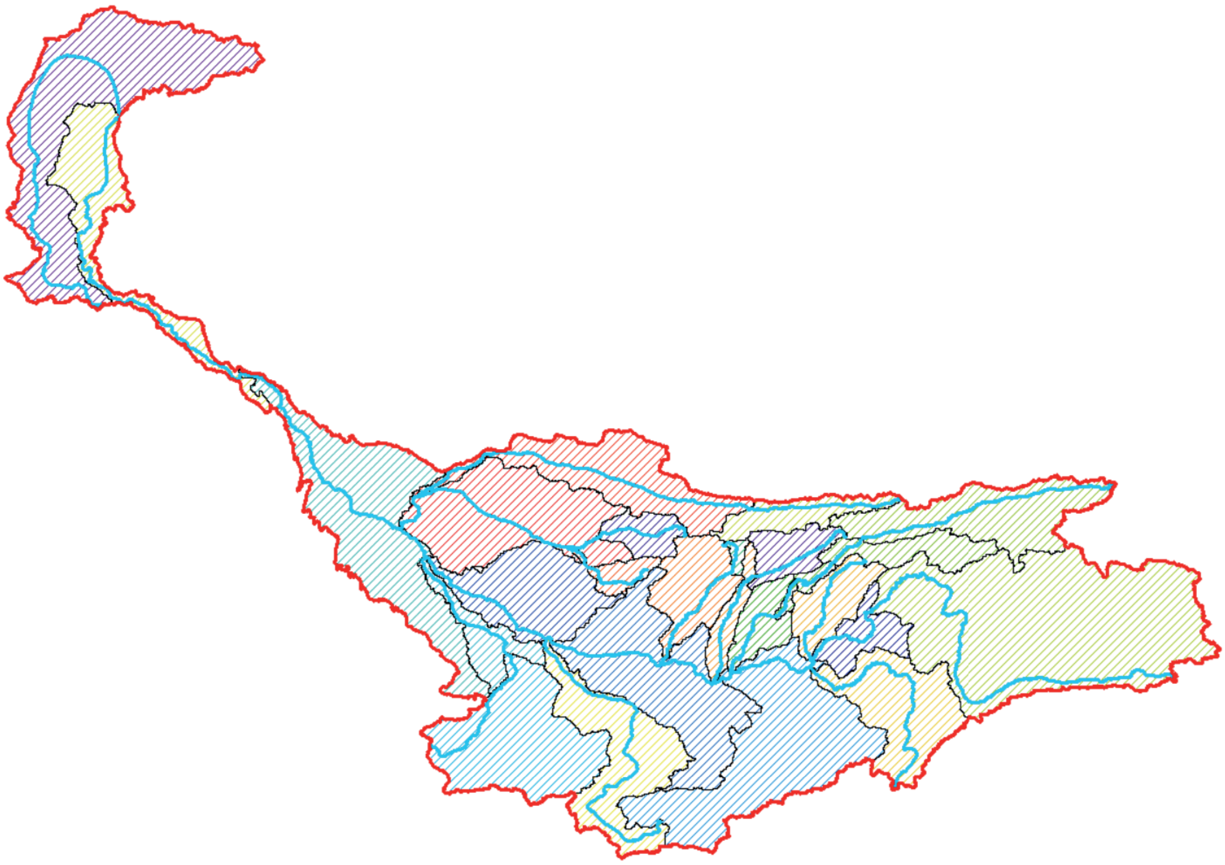

Figure 3. Spatial disaggregation of Amu Darya river basin into sub-catchments

LOW EMISSIONS ANALYSIS PLATFORM (LEAP)

General overview

The energy systems model used in the RDS analysis was built with three pieces of software: LEAP, the Next Energy Modeling system for Optimization (NEMO), and the Gurobi Optimizer solver. LEAP is the main component in this platform and provides user and application programming interfaces to the model. These support changing the model's inputs and formulas, calculating the model, and reviewing and visualizing results.[1], Although the energy systems model used in the RDS analysis is built on LEAP, NEMO, and Gurobi Optimizer, this report refers to it as the "LEAP model" for simplicity's sake.

LEAP scope and structure for Amu Darya

Model coverage and internal structure

The LEAP model simulates the energy systems of Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan from 2010 to 2050. It represents all sources of energy demand and supply in these countries, including all fuels or energy carriers[2]. The energy simulation extends from final energy demands through the transportation and distribution of fuels, fuel production, primary energy extraction, and energy trade. The model calculates GHG emissions from energy production and consumption (carbon dioxide, methane, and nitrous oxide) as well as the direct costs of energy demand and supply in some cases (electricity production, water pumping).

Each of the five Central Asian countries is represented as a separate region in the model. Most of the modeling of energy demand, energy supply, emissions, and costs is geographically aggregated to the regional level. For example, demands for heat are calculated for each region (country) rather than for provinces, cities, or other subnational areas within each country. The model was designed to integrate with the WEAP model for the Amu Darya and Syr Darya Basins, however, there are exceptions to this approach for three components of the energy systems with important implications for water: hydropower production, agricultural energy demand, and energy demand for water pumping. In these cases, the modeling within each country is further disaggregated by basin.

The LEAP model includes a historical period, for which it reproduces historical energy demand and supply, and projection years, for which it simulates the evolution of the national energy systems. In most cases (but depending on the specific variable), the historical period is 2010-2019, and projections run from 2020 to 2050. The model comprises multiple projections corresponding to different scenarios, including a baseline scenario and scenarios exploring particular policies (these are discussed in detail in section 4). The default time step in the model is annual, meaning that inputs and outputs are defined with annual resolution. However, for increased realism, the modeling of electricity demand and supply is performed with sub-annual time steps: 288 time slices per year, representing a typical 24-hour day in each month.

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[1] Source code and documentation are available through https://www.sei.org/tools/nemo-the-next-energy-modeling-system-for-optimization/

[2] The terms «fuel» and «energy carrier» are used interchangeably in this report.

Disaggregation and Simulation of Energy Supplies and Demands

LEAP supports disaggregating models by various user-defined categories in addition to geographic regions and time steps. The LEAP model for the RDS analysis takes advantage of this capability to further structure its simulation of energy supply and demand. Final energy demands are classified by sector/subsector and fuel, include Agriculture, Commercial, residential, and transport sectors (see Annex B for details on disaggregation).

On the supply side of the model, energy production is broken down by sector or industry, technology, and fuel (see Annex B for details on disaggregation).

For each sector/industry, the model represents energy use, energy production, and emissions. It also accounts for transfers of energy between sectors, changes in energy stocks or inventories, and losses in energy transportation, transmission, and distribution. The modeling of electricity supply separately represents major existing, planned, and potential hydropower facilities in the Amu Darya and Syr Darya Basins – 53 in all. These are connected to the WEAP modeling when the LEAP and WEAP models are run in integrated mode. Other electricity supply facilities are aggregated by technology (33 in total), including various coal, fossil gas, oil, nuclear, and renewable technologies (for a full list of HPP plants and technologies represented see Annex B).As part of its simulation of primary energy extraction, the LEAP model tracks reserves of non-renewable energy (coal, fossil gas, and oil) and annual potential or yields of renewable energy (biomass, hydro, solar, and wind).

A detailed description of modeling methods, input data and assumptions can be found in Annex B.

The model is designed to take projections of certain activity levels – volumes of water pumped – from the Activity water resources model. It is also designed to take projections of GDP and value added from the WAVE macroeconomic models (in the case of Kazakhstan and Kyrgyz Republic). In regions not covered by the macroeconomic models (Tajikistan, Turkmenistan and Uzbekistan), GDP and value added are projected based on trends and targets in national policies. The projection of households depends on historic household sizes and projected population from UN Department of Economic and Social Affairs (2019). Vehicle and tonne-kilometers are generally projected using their statistical relationship with GDP, unless national policies state a different future target or there is no statistically significant relationship with GDP (in which case the last observed historical value is held constant).

Future values of the drivers of changes in energy intensity are projected using complementary techniques. Personal income is calculated from projected population and GDP, while future fuel prices are based on prices and growth rates in International Energy Agency (2021d) and National Renewable Energy Laboratory (2021). Heating and cooling degree days are taken from climate model runs performed for the 6th Climate Model Intercomparison Project (CMIP6).

With respect to energy supply, the model is configured to reproduce historical records, notably International Energy Agency (2021c). Future energy supply is then projected with several simulation methods. Future electricity production is calculated via least cost optimization in NEMO. Subject to technical limits and accounting for cost and performance characteristics of power production options, the model finds the least costly way to supply electricity in every year and time slice. It covers both capacity expansion and dispatch – choosing what new production capacity to build and how to utilize the capacity that exists at each time step. SEI calibrated the electricity optimization routine to historical energy balance data for 2010-2019. There are some limits on the technologies the model can choose to build. Wind and solar capacity is limited by the potential of these resources; hydropower and biogas additions are restricted to replacing retiring facilities and building planned new hydropower facilities; and fossil and nuclear capacity is unlimited. The model assumes that historically observed energy imports and exports continue in the future. These imports and exports occur regardless of shortages or surpluses in the supply system. For future supply from other energy-producing sectors, the model performs a simple simulation in which the technologies and input fuels that have historically satisfied energy demands are assumed to continue doing so.

Model outputs

The model can generate a wide variety of outputs related to the Amu Darya countries' energy systems. These include energy demands by sector and fuel, total primary energy supply, domestic production of different energy carriers, energy imports and exports, non-renewable energy resource depletion, unmet energy requirements, and greenhouse gas emissions from energy production and consumption. In the power sector, generation, hourly dispatch, capacity additions and retirements, peak load, capacity factors, reserve margins, curtailment of renewables, and production costs can be reported. All of these results can be segmented by region, year, and other dimensions.

A key output for the Amu Darya analysis is dispatch of hydropower plants in the Amu Darya Basin. When the model is run in an integrated fashion with the WAVE water resources model, the water model determines the availability of water for hydropower, and the LEAP/NEMO model calculates how much water is actually used for hydropower. The two models iterate to seek convergent solution.

MACRO (macroeconomic model)

General overview

Macro is an open-source macroeconomic model. It is designed to be used with LEAP through the LEAP-Macro extension. It is thoroughly documented online.[3] The code is open-source and can be obtained through GitHub; a link to the source code can be found on the documentation site.

Macro is an economic simulation model but is not an economic planning model. Rather, the purpose of the combined LEAP-Macro model is to make internally consistent economic scenarios for LEAP. In a standard LEAP model, economic activity levels are specified externally (e.g., GDP and sector value added). But energy investment – calculated by LEAP – contributes to GDP. That creates a two-way link between the energy sector and the rest of the economy. In LEAP-Macro, economic activity levels are simulated, while energy investment contributes to aggregate demand.

The Macro model is built upon a set of accounting relationships, which are initialized using national supply and use tables (see Figure 4). The model then simulates a sequence of dynamic interactions. Details are available in the online documentation. For the purposes of this report, the sequence can be summarized as:

- First, expected and historical demand, both domestic and export, partly determines investment; investment also depends on profitability, which depends on wages and prices for goods and services.
- Second, investment adds to total final demand.
- Third, demand for intermediate goods and services combines with final demand to yield domestic demand, which drives the economy forward.

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[3] After this project began, Macro was renamed the Adaptable Macroeconomic Extension for Sustainability Analysis (AMES). Documentation for AMES is available at: https://sei-international.github.io/AMES.jl/stable/ . In this text, we continue to refer to the model as Macro.

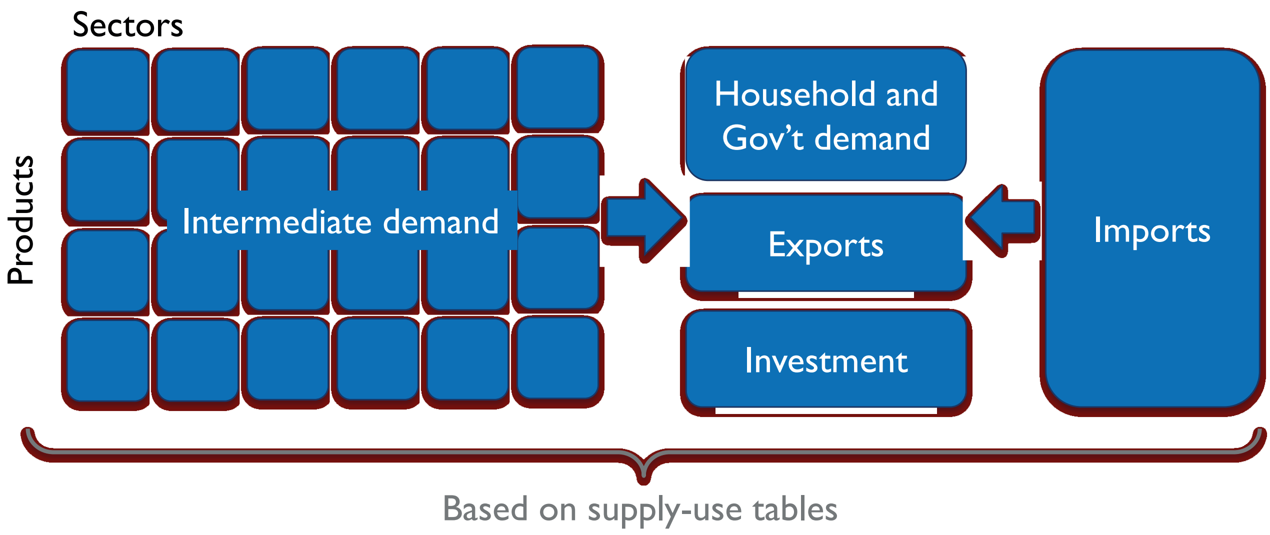

Figure 4. Structure of the underlying accounts in the Macro model

Macro for the Amu Darya

The Macro model requires data on intermediate demand – that is, purchases by industries of the products of other industries. These are recorded in national *supply and use* tables. Furthermore, the present Activity used only publicly available data. This severely limited the number of countries for which a Macro model could be constructed. Of the riparian countries within the Amu Darya basin, only Kyrgyz Republic provides publicly available supply and use tables. Uzbekistan prepares such tables but does not publish them.[4] Tajikistan does prepare tables, but the published versions are incomplete. Turkmenistan does not prepare such tables. Thus, for the LEAP and WEAP analyses, in the Amu Darya, Macro models were prepared and calibrated for Kyrgyz Republic only.

APPROACH TO MODELING – COMBINING MODELS

Overview of the approach

The modeling approach of this Activity is a combination of RDS and WEFE nexus. The Activity specifically combines the water planning and management model (system) built with the WEAP modeling platform with the energy planning model (system) built with LEAP and NEMO, and the macroeconomic Macro model that is designed to work with LEAP. The LEAP/NEMO, WEAP, and Macro models are run iteratively until the results converge.

Both LEAP and WEAP can address basic aspects of water and energy planning in isolation. For example, LEAP can be used to model hydropower, but this system does not account for water scarcity or dry years as a possible challenge. WEAP, meanwhile, can calculate how hydropower potential might change under different water supply scenarios, but does not allow for the study of how hydropower fits into the overall energy system.

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[4] A published set of tables for Uzbekistan for 2014 was prepared in the course of a Master's thesis (available from https://www.econstor.eu/bitstream/10419/232286/1/1752051408.pdf). However, the author of the thesis stated in conversation that the tables might not be suitable for this project and attempts to calibrate the model with the data-set showed that to be the case.

Thus, SEI has integrated these models so that they can give results that are more realistic as well as opening up opportunities for synergies and tradeoffs that would otherwise be missed in a more siloed approach.

Through the integration, WEAP and LEAP can exchange key modeling parameters and results, such as hydropower generation or water requirements for unit cooling, etc. Together, they can represent changes in conditions in both water and energy systems and allow for a more comprehensive water-energy model that considers different sectors of the economy simultaneously.

Both WEAP and LEAP rely on economic drivers, such as GDP or value added, in addition to demographic drivers. However, they also provide outputs that affect economic performance. The influences considered in this analysis include: investment expenditure, which can either stimulate the economy or crowd out private investment; lower production from water-dependent sectors during drought periods; the value of natural gas, coal, and crude oil production; and the value of agricultural output. These influences were captured by Macro to represent feedbacks from water and energy systems into the broader economy. The revised economic drivers were then fed back to LEAP and WEAP. The combined models were run until convergence.

Details of the interlinkages

The iteration process was implemented in a custom Python script written by SEI. The script accepts a configuration file and reports progress in a log file. Results are available for examination in the LEAP and WEAP platforms and, for Macro, in text files. The script follows these steps:

- The script runs the Macro model, generating values for economic drivers (value added and GDP), which are passed to LEAP;
- LEAP passes those drivers, with population, to WEAP (without calculating);
- WEAP runs, generating results for water demand and supply:
    - Hydropower availability, based on hydrology, is passed to LEAP;
    - Crop production and industrial water availability is passed to Macro;
- LEAP runs, generating results for the energy sector:
    - Hydropower generation is passed to WEAP;
    - Power sector investment, as well as coal and crude oil production, are passed to Macro;
- Macro runs, and the cycle continues from Step 1 until convergence: key results (particularly hydropower production) are compared from one run to the next, and if all are within a specified tolerance (assumed as 10%), then the process halts.

Overall, the integrated WEAP-LEAP-Macro model captures synergies between different sectors of the economy, both direct and indirect, as shown in Figure 5 below.

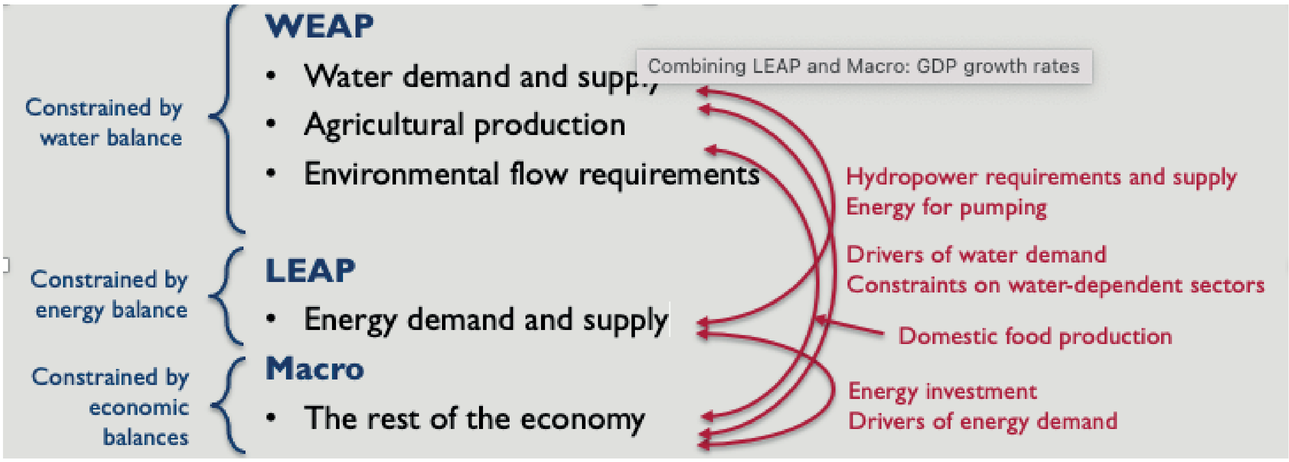

Figure 5. Interrelationships between sectors

Using both systems together, decision-makers can now examine how individual water and/or energy management choices might affect other sectors of the economy. This allows the assessment of potential future scenarios and outcomes against current policies, goals, and objectives. If one approach leads to unacceptable outcomes, alternative scenarios, strategies and measures can be explored.

REGIONAL SCENARIOS IN WEAP AND LEAP MODELS

Narrative pathways

As mentioned earlier, the Activity ran a series of national and regional consultations with the WEFE-related ministries and agencies (water, energy, agriculture, environment, as well as foreign affairs and economy) and strategic and scientific-research institutes of the Amu Darya basin countries – Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan. The main goal of those consultations was to identify critical uncertainties, goals, data sources and, most importantly, to develop the regional scenarios (with the inclusion of national interests and priorities and different climate projections) for further analysis through the models. Further application of the siloed approach in modeling (separately WEAP or LEAP) and an integrated approach (WEAP-LEAP-Macro) demonstrated different results proving that an integrated understanding to planning brings more holistic and comprehensive results and should be used to achieve more sustainable results for overall sustainable development.

The regional consultations resulted in the development of 4 unique narrative pathways, presented below in Table 1, each with 2 different climate projections (described below in more detail) each for a total of 8 scenarios for further modeling.

Table 1. Overview of Narrative Pathways

Narrative pathways	Hydropower	Agriculture	Water Allocation	Ecosystems
Baseline (National interests)	Existing plus addition of Rogun and other planned HPP	• Cropped area fixed at 2020 levels • Yields follow past trends • Shift to higher value crops	Set in accordance with national priorities	Lowest priority
Agricultural Efficiency	Same as above	Baseline plus a range of investments to improve water use and yield - Reduced canal losses - Improved irrigation efficiency	Same as above	Same as above
Energy & Climate Policies	LEAP includes new energy and climate policy targets *WEAP is Informed by LEAP model*	Same as above in WEAP and LEAP is informed by the WEAP model	Same as above	Same as above
Cooperation	Same as above	Same as above	Dams in upper basin release to meet all downstream demands	Same as above

All 4 narratives were explored with the WEAP and LEAP models for the Amu Darya River Basin. These included a baseline narrative, representing current conditions and rules surrounding the management of water and energy resources within the basin, in combination of the full build-out of infrastructure plans representing the national interests of each country. The second narrative named Agricultural Efficiency targets increased water efficiency through reduced canal losses and improved irrigation practices. The third narrative, Energy and Climate Policies, includes new infrastructure to achieve greenhouse gas emission targets, increased efficiencies and additional energy and climate policies. The fourth narrative explores possibilities towards cooperation.

The starting point of each narrative uses the narrative that precedes it, such that narrative 2 includes all of the modeling assumptions made in narrative 1, narrative 3 includes all of the modeling assumptions made in narrative 2, and so on.

The narratives include existing WEFE-related policies, strategies and plans of each country, as well as potential activities that are now under discussion and not put in force yet. Thus, the results of this modeling exercise cannot be used for actual decision making and promotion. The main goal of the modeling was to demonstrate the benefits of applying the complex WEFE approach towards decision-making and prove that complex results can bring to different actions in comparison with siloed approach.

Details of the changes in WEAP and LEAP for each narrative scenario is given in Annex A.

Climate projections

The WEAP model for the Amu Darya basin incorporates climate projections from the CMIP6[5] ensemble to evaluate future water resource scenarios under varying climate conditions. WEAP includes automatic linkages to over 100 CMIP6 climate projections, encompassing four shared socioeconomic pathways (SSPs) across 27 different Global Climate Models (GCMs). These projections provide a robust basis for assessing how different climate futures might impact water availability, demand, and management strategies in the basin. By integrating this extensive range of climate data, the WEAP model can simulate and analyze the potential effects of climate projections on the Amu Darya's water resources, helping stakeholders make more informed and resilient water management decisions.

The graph below (Figure 6) show summary data of the Amu Darya river basin for 48 projections that include the moderate emissions reduction scenario (SSP 245) and high emissions scenario (SSP 585) (CMIP Phase 6 (CMIP6) - Coupled Model Intercomparison Project, 2022). There are 48 blue squares that indicate the average change in climate in the near term (2020-2040) relative to a historical period (1990-2010) and 48 red triangles that show the average change in the medium-term (2040-2060) relative to the same historical period.

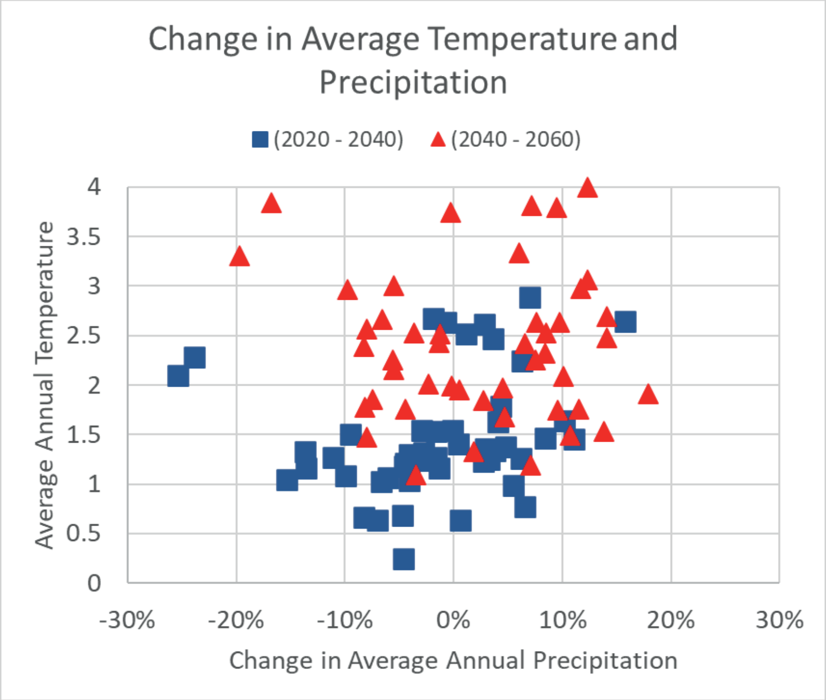

Figure 6. Projected changes in annual precipitation and temperature for the Amu Darya river basin

For the Amu Darya river basin these data suggest that precipitation in the near term and in the mid-term may range from a fifteen percent decrease to an eighteen percent increase over the average historical level (when outliers are removed). Overall, the average of these data suggests a slight (2%) decrease in precipitation over the historical in the near term and a moderate (5%) increase in precipitation in the medium term. These data also indicate that average annual temperature within the Amu Darya basin will increase for all projections, with most (i.e. projections within the inner two quartiles) suggesting an increase of 1 to 1.5 degrees C for the period 2020-2040 and an increase of 1.9 to 3.0 degrees for the period 2040-2060.

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[5] CMIP6, or the Coupled Model Intercomparison Project Phase 6, is a collaborative effort within the climate science community to compare and assess global climate models. Launched by the World Climate Research Programme (WCRP), CMIP6 involves multiple climate modeling centers worldwide. The project aims to improve our understanding of the Earth's climate system, enhance the reliability of climate projections, and provide valuable insights for policymakers. Researchers use CMIP6 to simulate various aspects of the climate, such as temperature, precipitation, and atmospheric composition, enabling comprehensive analyses of potential future climate scenarios.

Two representative climate projections were selected to capture the range of potential climatic conditions in the Amu Darya basin: one wet and one dry. The selection process for the representative dry climate projection involved identifying the projection that was closest to the 10th percentile in average precipitation and the 90th percentile in average annual temperature. This ensures that the dry scenario reflects a combination of low precipitation and high temperatures. Conversely, the representative wet climate projection was chosen by selecting the projection closest to the 90th percentile in average precipitation and the 10th percentile in average annual temperature, representing conditions with higher precipitation and cooler temperatures. These representative projections provide a robust basis for analyzing the impacts of varying climate extremes on the basin's water resources.

Combining narrative pathways and climate projections for 8 scenarios

The four narratives were combined with two climate projections for a total of 8 scenarios, as shown in Table 2 below. This combination of different policy narrative pathways with different possible climate projections can support the identification of more robust pathways for the countries of the Amu Darya.

Table 2. 8 scenarios implemented in the integrated WEAP-LEAP-Macro models

Narrative pathways	Climate projections
S1. Baseline (National interests)	Wet
	Dry
S2. Agricultural Efficiency	Wet
	Dry
S3. Energy & Climate Policies	Wet
	Dry
S4. Cooperation	Wet
	Dry

These scenarios are explored in detail in the analyses and results presented in the following section.

ANALYSES AND RESULTS

LEAP RESULTS

LEAP Results of integrated approach under the Baseline pathway

Over the coming three decades, GDP in the four riparian countries of the Amu Darya is projected to at least double (2020-2050, Figure 7). In response to this substantial economic development, as well as population growth, regional energy demand will grow by more than 3-fold under the Baseline policy pathway (S1). Modeling results predict energy demand to grow most substantially in Uzbekistan (3.7-fold to 5 Billion PJ), followed by Tajikistan and Turkmenistan (both 2.5-fold). Energy demand in Kyrgyz Republic will grow 1.5-fold over the same period.

Results show only marginal differences in energy demand between the dry and wet climate scenarios. The different climate projections primarily affect energy demand in the residential sector whose energy demand in response to cooling and heating needs differs slightly (<1% between 2020-2050).

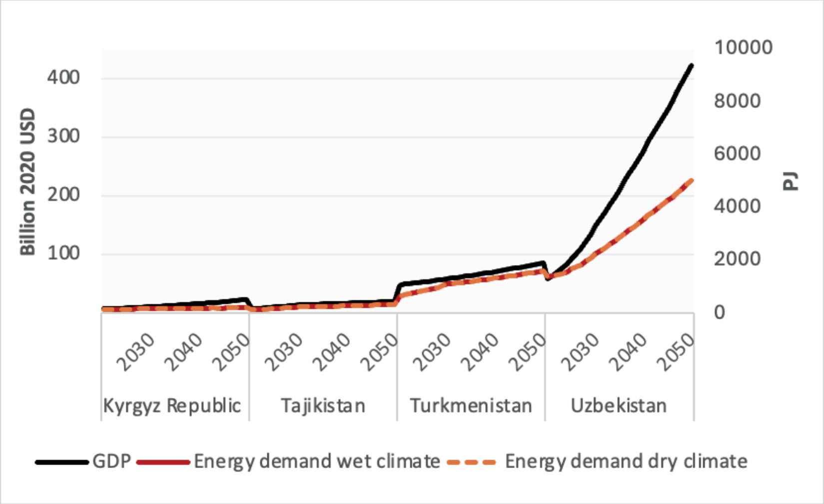


Figure 7. Evolution of national GDP (black) and energy demand (shades of orange) in Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan between 2020-2050

Whereas in Tajikistan and Uzbekistan, increases in energy demand are driven by industrial growth (39% and 51% of total energy demand, ca. 2050), increases in energy demand are dominated by the residential sector Kyrgyz Republic, and the commercial sector in Turkmenistan (Figure 8). While transport and agriculture play a minor role in total energy demand in all countries, the agricultural sector in Uzbekistan is projected to experience one of the highest growth rates of all sectors (6.9-fold).

Natural gas, oil products and electricity are the three largest components of final energy demand in these countries. Natural gas contributes 5%, 4%, 75%, and 55%; oil products contribute 39%, 32%, 19% and 11% and electricity contributes 32%, 40%, 5% and 21% to total energy demand in Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan, respectively.

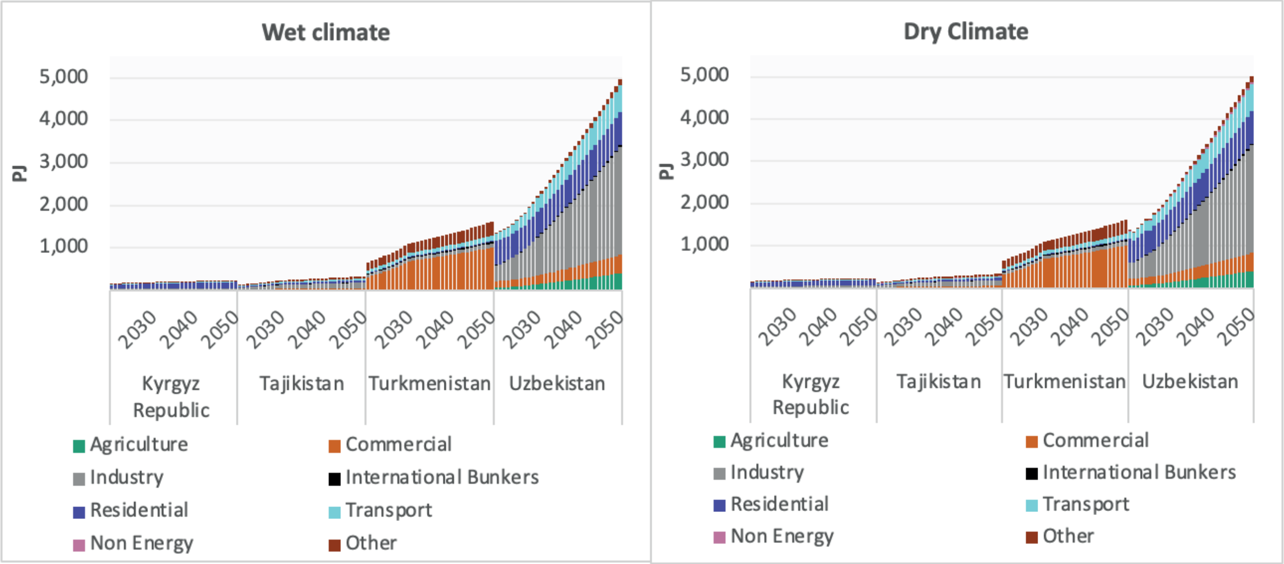


Figure 8. Energy demand by country and sector under the wet and dry climate projection between 2020-2050

Satisfying growing energy demand under the Baseline scenario (S1) requires 113-117 GW additional electricity production capacity development across 4 riparian countries between 2020-2050, of which 28 GW will be needed in Kyrgyz Republic, 18 GW in Tajikistan, 14GW in Turkmenistan and 71 GW in Uzbekistan. Model results show that under the Baseline scenario (S1) half of newly developed capacity will be coal capacity (59-62 GW) due to its low fuel cost compared to alternative technologies in all countries with coal reserves (Uzbekistan, Kyrgyz Republic and Tajikistan). In Turkmenistan, which has no coal reserves, 70% of new capacity developments in are either solar or wind technologies (6 and 4 GW, respectively).

In addition to coal, the model results show important capacity developments of hydropower (11 GW), which is added based on national plans, as well as oil (13-16 GW), fossil gas and solar (both 8-9 GW). In addition, 2 GW of new nuclear capacity would be developed in Uzbekistan. The majority of fossil gas and dual gas oil developments occur between 2035-2050, when these technologies become more affordable.

Hydropower is key to national electricity development plans in the region, and 10.9 GW of hydropower developments planned are planned in the Kyrgyz Republic and Tajikistan (5.4 and 5.1 GW, respectively). 4.0 GW of the 10.9 GW of new hydropower capacity will be developed in the Amu Darya Basin, almost entirely in located in the Tajik region of the Amu Darya Basin (3.9 GW).

Model results show that under the dry climate projection compared to the wet climate projection, an additional 4 GW of electricity production capacity is required to meet energy demand. This additional need for backstopping capacity is primarily driven by lower reliability of hydropower under the dry climate projection.

Overall, corresponding to energy demand, annual electricity generation grows substantially between 2030-2050 (2.7-fold, Figure 9). In Kyrgyz Republic, electricity supply grows from 13.2 to 23.6 TWh; in Tajikistan from 20.5 to 48.3, in Turkmenistan from 23.1 to 24.6 and in Uzbekistan from 64.7 to 352.7 (under the wet climate projection). Over time, fossil gas technologies are replaced with solar and wind technologies in Turkmenistan, and coal and nuclear technologies in Uzbekistan.

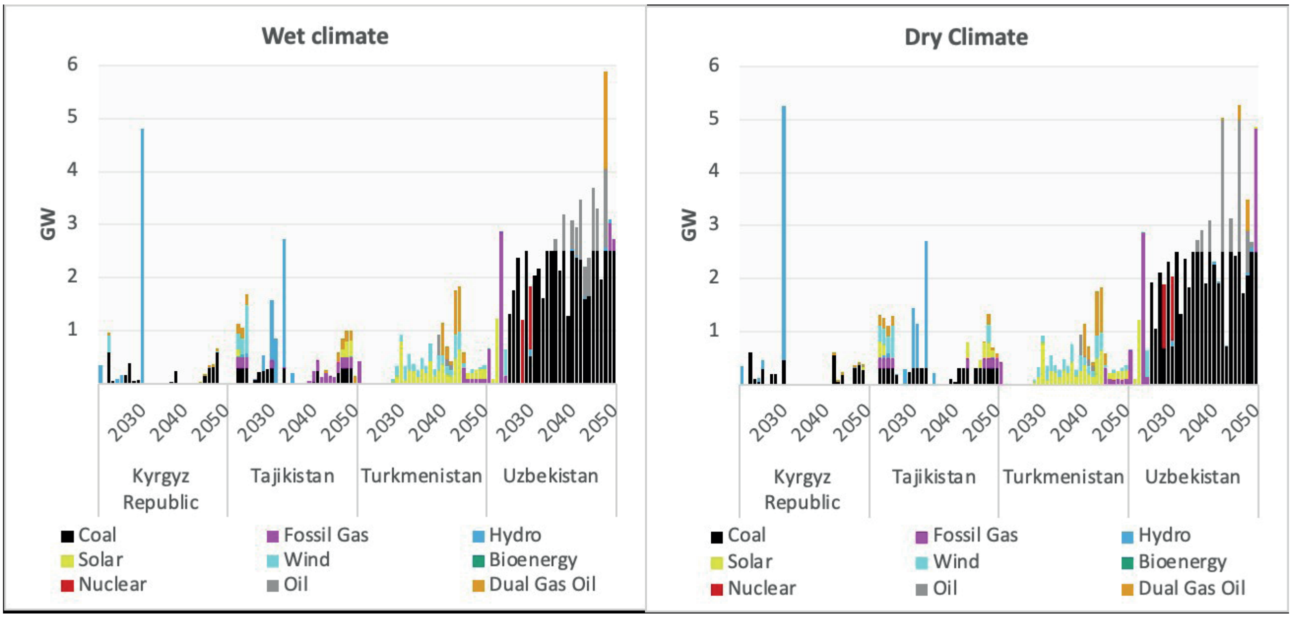


Figure 9: Capacity additions by technology and country under the wet and dry climate scenarios between 2020-2050

The mix of modeled annual electricity supply is substantively caused by decreased water availability under dry climate projection. In Kyrgyz Republic and Tajikistan, hydropower provides 53 and 54% of total electricity supply, respectively, under wet climate projection, but only 42% and 39% under the dry climate projection (2020-2050, *Figure 10*). The hydropower shortfall under the dry climate projection is primarily compensated by coal.

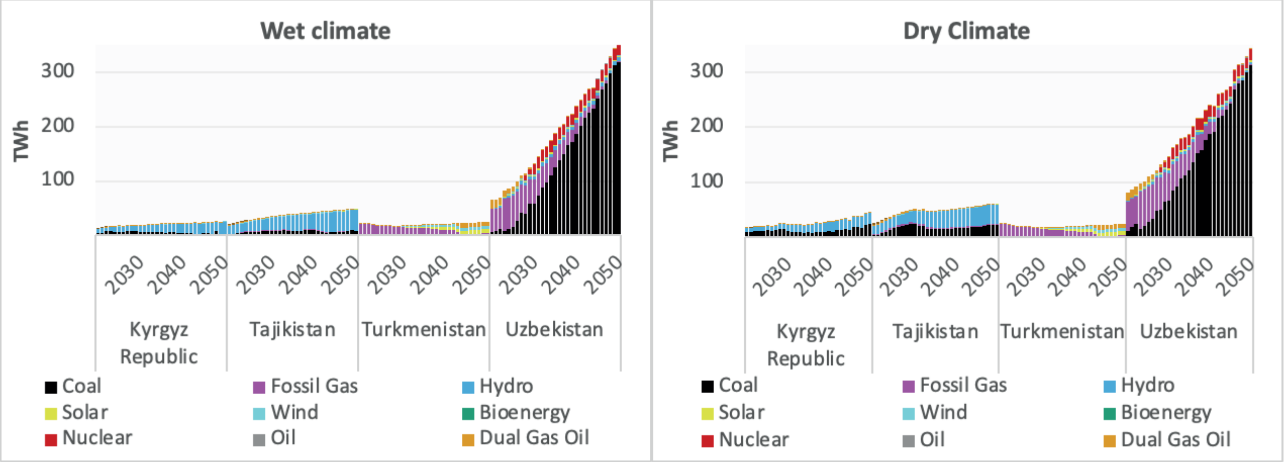


Figure 10: Electricity supply by fuel in Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan under the wet and dry climate projections

In addition, different climate projections may cause substantial interannual variation in electricity supply. In the dryest years in both dry and wet climate projections, hydropower contribution to total electricity supply lies 15-25% below typical hydropower generation.

More than 97% of hydropower in the Amu Darya Basin is generated in Tajikistan (Figure 11). Under the wet climate projection, hydropower generation grows >2-fold to 36 TWh yr^{-1} consistent with substantial hydropower capacity developments in the region. The Nurek hydropower station is the most important hydropower plant in the Amu Darya basin, accounting for 70% of basin-wide generation currently.

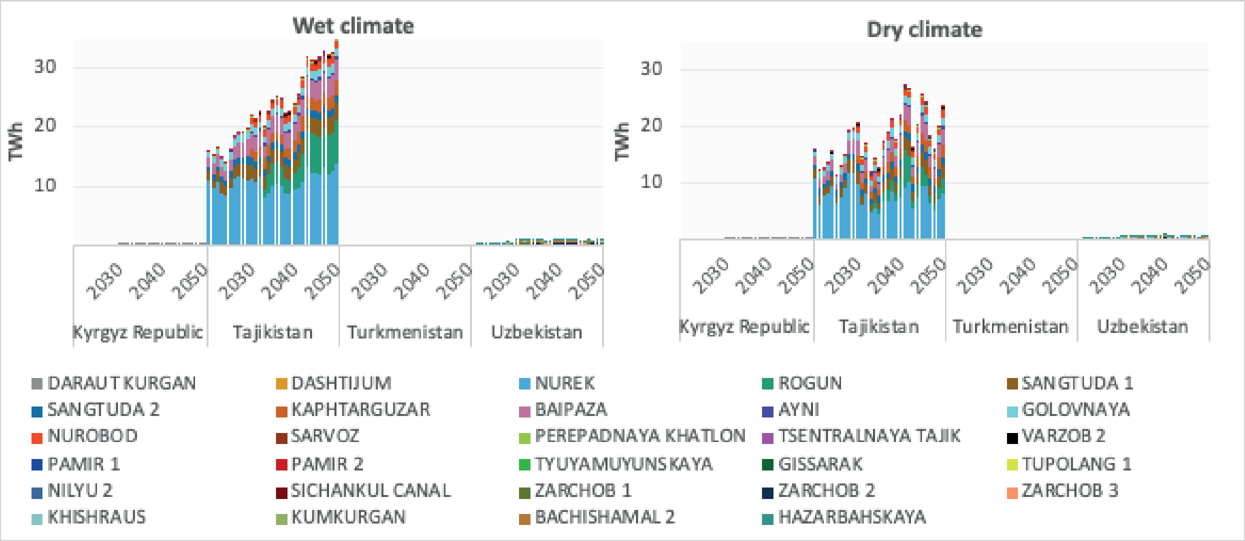


Figure 11: Hydropower generation in Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan under the wet and dry climate projections

Under the dry climate projection, capacity expansion does not translate to similar increases in hydropower generation. Instead, hydropower generation is much more variable, driven by the largest hydropower plants, Nurek and Rogun.

Our findings show that under different climate projections and without proper energy-efficient technologies in place, new hydropower capacity development may not have the expected electricity outputs and create a substantial shortfall in hydropower generation to meet the demands because of water scarcity and interannual variability. This has important implications for the region's energy systems. It will require additional backstopping capacity development, which will include substantial amounts of fossil fuels unless countermeasures are taken that consider both potential climate variations (dry and wet projections) and climate mitigation.

Comparison of Baseline pathway results from integrated modeling with stand-alone LEAP modeling

Compared to the LEAP-stand-alone model of the Amu Darya, the integrated modeling platform provides important insights into the implications of different climate projections and competing water uses for hydropower generation, and how those affect required capacity developments and investment costs.

Figure 12 shows the difference in electricity supply and capacity additions in LEAP stand-alone model compared to integrated modeling. Positive values indicate that the stand-alone LEAP model underestimates electricity supply or capacity additions, whereas negative values indicate that the stand-alone LEAP model overestimates electricity supply or capacity additions.

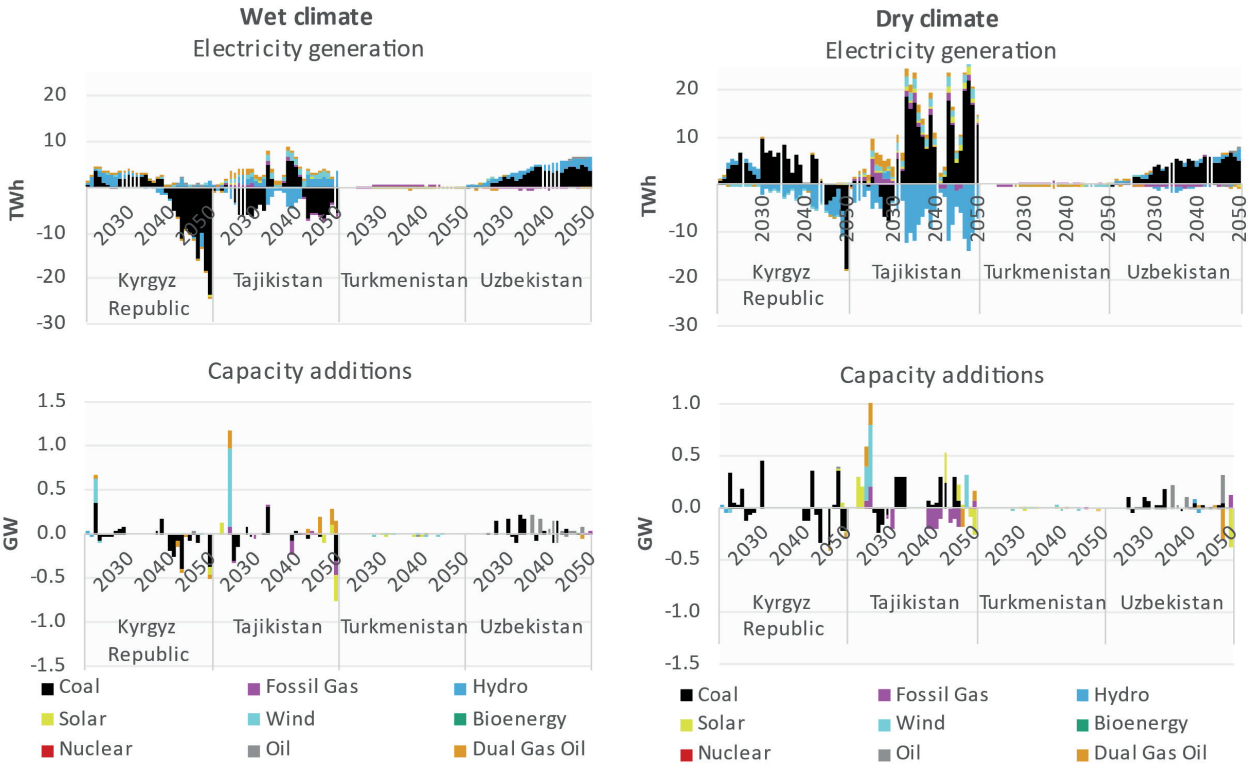


Figure 12. Difference in electricity supply and capacity additions in LEAP stand-alone model compared to integrated modeling. Positive values indicate that the stand-alone LEAP model underestimates electricity supply/capacity additions, whereas negative values indicate that the stand-alone LEAP model overestimates electricity supply/capacity additions

The modeling results indicate that stand-alone LEAP modeling, which is blind to interannual variability in water availability and competing water demands, systematically underpredicts the need for electricity generation from coal and associated capacity development. This is especially apparent under the dry climate projection, where the LEAP stand-alone model underpredicts annual coal-based electricity generation by up to 22 TWh yr^{1} (cumulative shortfall of 400 TWh, 2020-2050). While overall less coal generation is needed than predicted by the stand-alone LEAP model under the wet climate projection (-0.9TWh net), there are still some countries and years where an additional 6 TWh of coal-based generation are required to meet demand (ca. 2038, Tajikistan). Cumulative hydropower shortfalls under the dry climate projection that are overlooked by the stand-alone LEAP model amount to 210 TWh (2020-2050, all four countries).

Integrated modeling that considers impacts of different climate projections on water resources, including interannual variability, and competing water demands is especially important for upstream countries that rely heavily on hydropower and are hence more vulnerable to these changes, like Kyrgyz Republic and Tajikistan. In both countries, shortfalls in hydropower generation are backstopped with fossil fuel-based power generation, primarily coal, as well as wind and solar power. In Uzbekistan, stand-alone modeling underpredicts energy requirements by 2% (ca. 2050) linked to increased irrigation requirements caused by warming temperatures. Here also, decreases in hydropower generation in dry years are backstopped with additional coal generation.

Ensuring that the electricity generation requirements can be met requires additional capacity to be developed for different technologies (and at different times) than indicated by the stand-alone LEAP model (Figure 18, Capacity additions). Under the dry climate projection, additional coal (2.5 GW), wind (1.3 GW), solar (1.2 GW), oil (0.9 GW) and dual gas oil (0.6GW) t are needed (0.8) capacity and associated investments are needed.

Not considering impacts of different climate projections on water resources and competing water demands on energy systems may result in misplaced investments of as much as 8.3 Billion in 2020 USD dry climate projection (Table 3). Financial risks associated with misplaced energy systems investment are greatest in Tajikistan due to its dependence on hydropower (5.39 Billion 2020 USD), and Uzbekistan due to the size of its energy system (2.31 Billion 2020 USD).

Table 3. Misplaced investments costs in Kyrgyz Republic Tajikistan, Turkmenistan and Uzbekistan, as indicated by integrated modeling compared to stand-alone LEAP modeling. Positive values indicate that the stand-alone LEAP model underestimates investment, negative values indicate an overinvestment in capacity of that technology

	Kyrgyz Rep. Billion USD_{2020}	**Tajikistan** Billion USD_{2020}	**Turkmenistan** Billion USD_{2020}	**Uzbekistan** Billion USD_{2020}
Coal	-1.67/0.28	-0.87/2.48	0/0	2.22/1.55
Fossil Gas	0/0	-0.11/-0.57	0/0.01	0.03/0.04
Hydro	-0.01/-0.01	0/0	0/0	0/0
Solar	-0.03/0.02	-0.02/0.39	0.03/0.04	0/0.13
Oil	0.01/0	0/0	0.02/0	0.49/0.39
Dual Gas Oil	-0.07/-0.06	0.43/0.19	0/0.01	0.03/0.2

These findings clearly illustrate the need and benefits of integrated energy and water allocation modeling for developing strategic policy planning around water and energy that is robust to various climate projections.

Agricultural efficiency / Energy policies

We explore the potential of agricultural efficiency and improved agricultural practices on Agricultural Efficiency pathway (S2) and Energy and Climate Policies pathway (S3) on the Amu Darya region's energy system.

Under S2, modeling results show minor decreases in final energy demand from more efficient irrigation practices (Figure 13). Under the Energy and Climate Policy pathway (S3) final energy demand decreases more substantially thanks to energy and climate mitigation policies, including energy efficiency and electrification measures following national plans in all four riparian countries. The impact of these measures is most pronounced in Uzbekistan and Tajikistan, where final energy demand decreases by 24% and 20%, respectively. The main sectors affected are industry, residential, and transport. 43% of cumulative final energy demand reductions arise from reductions in demand for natural gas, followed by electricity and oil products (17% and 16%, respectively). Like under the Baseline pathway (S1), differences in final energy demand between wet and dry climate projections are minor and arise from higher energy demand in the residential and agricultural sectors.

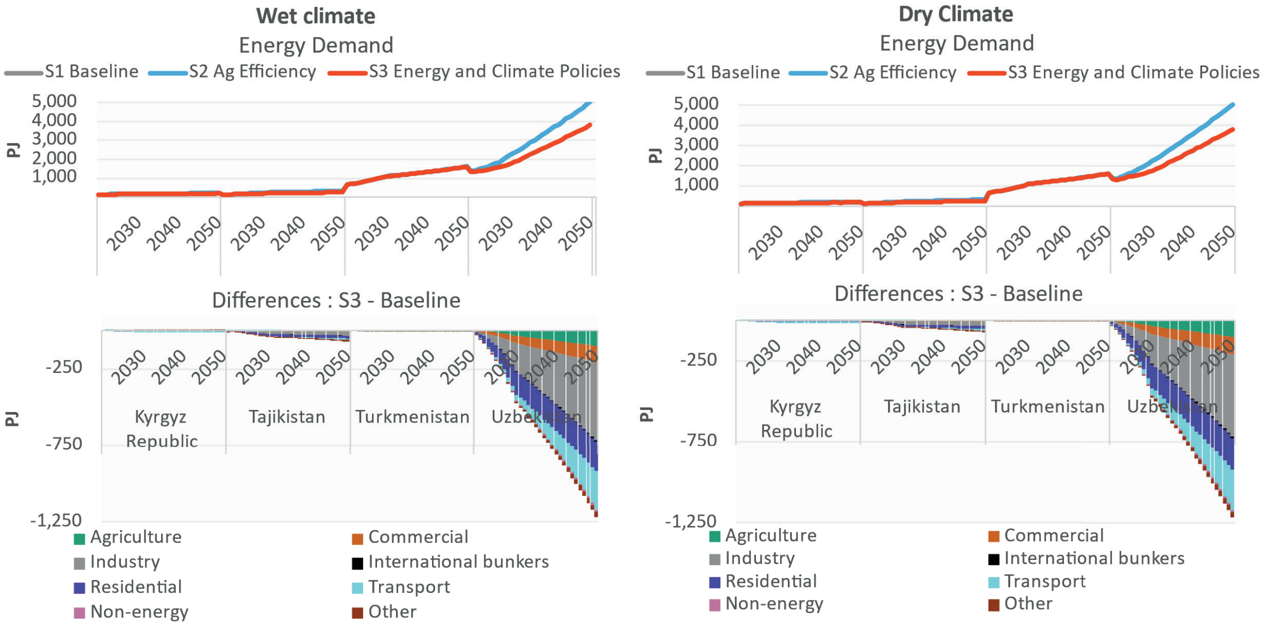


Figure 13. Final energy demand in Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan under the Agricultural Efficiency and Energy and Climate Policies pathways (S2 and S3), and differences between Energy and Climate Policies pathway (S3) and Baseline (S1) under the wet and dry climate projections

Electricity supply shows similar decreases under the Energy and Climate Policies (S3) pathway compared to the Baseline as final energy demand (Figure 14). Electricity generation under the Energy and Climate Policies pathway is 1%, 13%, 6% and 19% lower in Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan compared to the Baseline (ca.2050). The decrease in electricity supply of 1000 TWh in Uzbekistan is primarily due to a reduction in coal-based electricity, partially replaced with solar, wind and hydro power.

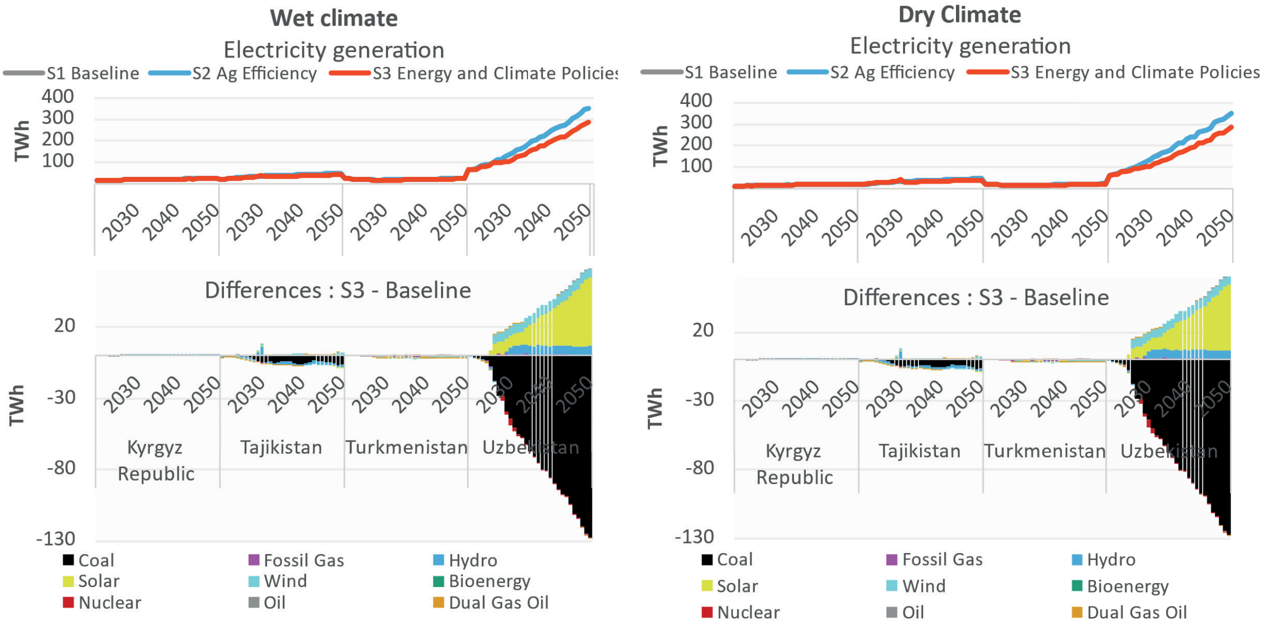


Figure 14: Electricity generation in Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan under the Agricultural Efficiency and Energy and Climate Policies pathways (S2 and S3), and differences between Energy and Climate Policies pathway (S3) and Baseline (S1) under the wet and dry climate projections.

The measures under S2 and S3, and the shift away from coal to renewables lead to reductions in greenhouse gas emission of 600 Million t CO_2eq (2020-2050). 2050 emissions under the combined Agricultural Efficiency and Energy and Climate Policies pathway (S3) are 20% below emissions in the

Baseline pathway (S1) (Figure 15). Emission reductions compared to Baseline are 20%, 30%, 0% and 19% in Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan, respectively (ca.2050).

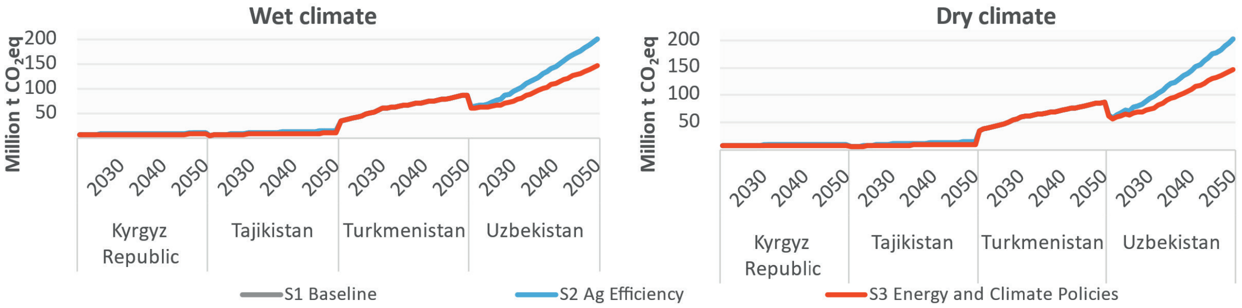


Figure 15: GHG emissions in Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan under the Agricultural Efficiency and Energy and Climate Policies pathways (S2 and S3) under the wet and dry climate projections.

The changes in electricity generations, have important implications for capacity requirements and hence investment costs. Under the wet climate projection, the implementation of S2 and S3 requires additional 3.25 Billion USD of investments in capacity developments in Uzbekistan and 0.05 Billion USD in Kyrgyz Republic, but less investments in Tajikistan and Turkmenistan (0.26 and 0.64 Billion USD of savings, respectively, Figure 16). This is due to less electricity generation being required as a result of energy and agricultural efficiency measures. Under the dry climate projection, more investments are required in Uzbekistan and Tajikistan to achieve climate mitigation goals, as less clean hydropower generation is available (3.78 Billion USD and 1.37 Billion USD total investment costs). Differences in investments needed in Kyrgyz Republic and Turkmenistan in the dry compared to the wet climate projection are small (<0.02 Billion USD).

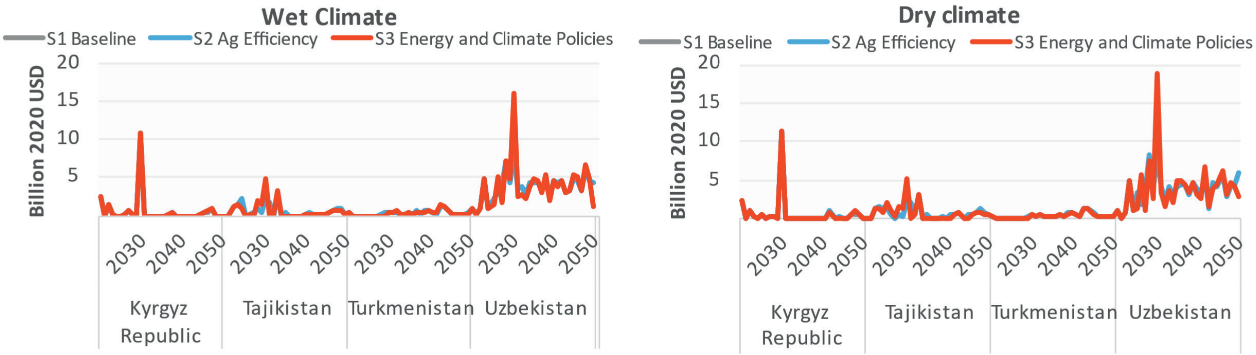


Figure 16: Investments costs in Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan under the Baseline, the Agricultural Efficiency, and the Energy and Climate Policies pathways (S2 and S3).

Cooperation

Prioritizing releases for agriculture in summer months, as explored in the Cooperation pathway (S4) substantially changes the electricity supply mix as hydropower generation is deprioritized in the region. Decreasing hydropower generation is backfilled with coal and wind in Kyrgyz Republic, primarily wind in Uzbekistan, and a mix of fossil fuels wind and solar in Tajikistan (Figure 17).

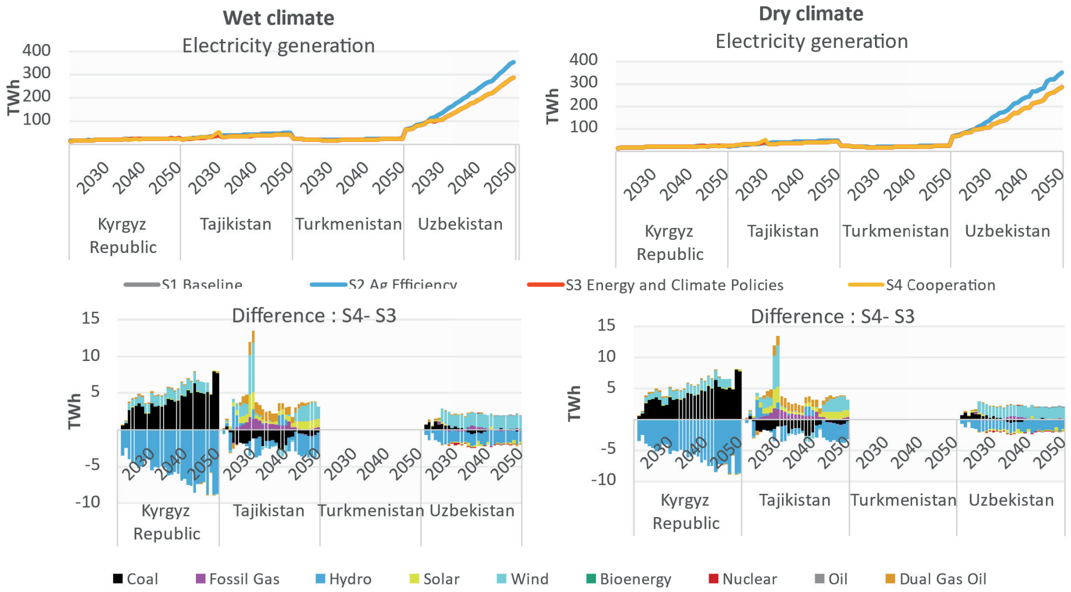


Figure 17. Electricity generation in Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan under the 4 policy pathways, and differences between the Cooperation pathway (S4) and the Energy and Climate Policies pathway (S3), under the wet and dry climate projections

This has important implications for investment costs and GHG emissions. Under the Wet Climate projection, where reliance is especially heavy on hydropower generation an additional 10.9 Billion USD of investments are needed (Figure 18). 53% of these investments occur in Tajikistan, which is most reliant on hydropower, and 34% and 13% in in Kyrgyz Republic and Uzbekistan, respectively. Investments would primarily be used to increase wind (8.0 Billion USD), coal (1.9 Billion USD) and solar (1.1 Billion USD) capacity.

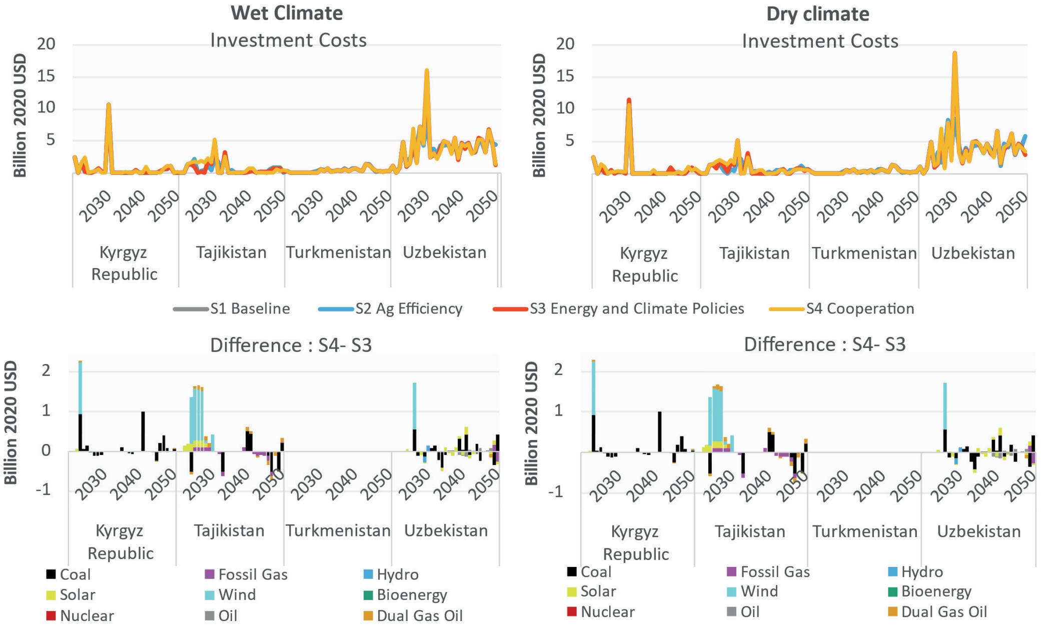


Figure 18: Investment costs in Kyrgyz Republic, Tajikistan, Turkmenistan and Uzbekistan under the 4 policy pathways, and differences between the Cooperation pathway (S4) and the Energy and Climate Policies pathway (S3) under the wet and dry climate projections.

Importantly, additional investments under the dry climate projection are much lower (7.4 Billion USD), as there is substantially more variability and uncertainty around the availability of water for hydropower preventing hydropower capacity to be fully employed in S1, S2 and S3. This means, that less benefits in from increased agricultural production in downstream countries can offset costs incurred by upstream countries agreeing to prioritize water releases for irrigation. Given future uncertainty related to different potential climate projections, costs to upstream countries as a result of effecting a cooperation scenario between might in fact be lower than expected. Impacts of reduced and more variable precipitation, and increased temperatures suggest that future hydropower availability is lower than indicated by historical hydropower generation. At the same time, other environmental costs, like increases in GHG emissions from increased coal (93-110 Million t CO2eq), fossil gas (10-11 Million t CO2eq) and dual gas oil (8-19 Million t CO2eq) also need to be considered in pathways that de-emphasize hydropower generation.

In summary, modeling results indicate that as the four riparian countries of the Amu Darya basin develop over the next three decades energy demand and electricity supply will grow 7-fold and require substantial new capacity developments. New hydropower capacity plays an important role in national plans, especially in Tajikistan, but impacts of potential different climate projections on water availability together with increases in water demands across the region indicate that the new hydropower capacity developments might experience substantial variability and shortfalls going forward. These will need to be compensated by additional fossil and renewable energy capacity in all four riparian countries. Improved agricultural practices and energy and climate mitigation policies have the potential to reduce the need for additional capacity, and hence costs. Improved cooperation around water between upstream and downstream countries provides an opportunity to improve agricultural outcomes, but increases required investments in the energy system, as well as GHG emissions.

Stand-alone energy systems models, like the stand-alone LEAP model of the Amu Darya, can only provide limited insight into these issues as they lacks spatial information of hydrology and water allocation which have important impact on the energy system, especially in upstream countries that rely heavily on hydropower. Our results show that weighing the costs and benefits of different policy pathways and their robustness to variety of potential climate projections requires integrated assessments of the energy-food-water system.

WEAP RESULTS

This results section presents the findings from the Amu Darya WEAP model in two distinct operational modes: standalone and integrated. In the standalone mode, WEAP functions independently, simulating water resource scenarios without any interaction with the LEAP energy planning model. This mode provides insights into water allocation and management based solely on the hydrological and infrastructural parameters set within WEAP.

In the integrated mode, WEAP is coupled with LEAP to create a more comprehensive analysis of the water-energy nexus. In this mode, WEAP first estimates the maximum potential hydropower generation based on available water resources and passes this information to LEAP. LEAP then utilizes these estimates to determine the optimal dispatch of energy from various sources, including hydropower. The actual amount of hydropower dispatched by LEAP is then fed back into WEAP. If LEAP does not dispatch the full hydropower potential estimated by WEAP, it indicates greater flexibility in managing water supplies. This integrated approach allows for a more nuanced understanding of how water and energy systems interact and how different management strategies can affect both sectors

Different climate projections effects on glaciers, river flows, and crop water requirements

The results for changes in glacier volume, river flow, and crop water requirements are presented first to provide a clear understanding of how different climate projections impacts the water resources in the Amu Darya basin. These results are crucial as they highlight how these processes are affected solely by climatic factors and are independent of any management interventions.

The WEAP model's results for the change in glacier volumes within the upper portion of the Amu Darya basin reveal significant reductions over the coming decades (Figure 19). Initial conditions in 2020 estimated the total glacier volume at 533 cubic kilometers. Under a historical climate sequence, this volume is projected to decrease by 11 percent by 2050. However, both the Dry and Wet climate projections indicate a more pronounced decline, with the total glacier volume decreasing by 19 percent by 2050. Notably, the increased rate of glacier melt under the Dry projection helps to compensate for the lower precipitation levels, helping to explain some of the results explored later in this document. These findings highlight the substantial impact of different climate projections on glacier melt, which is crucial for understanding future water availability in the basin.

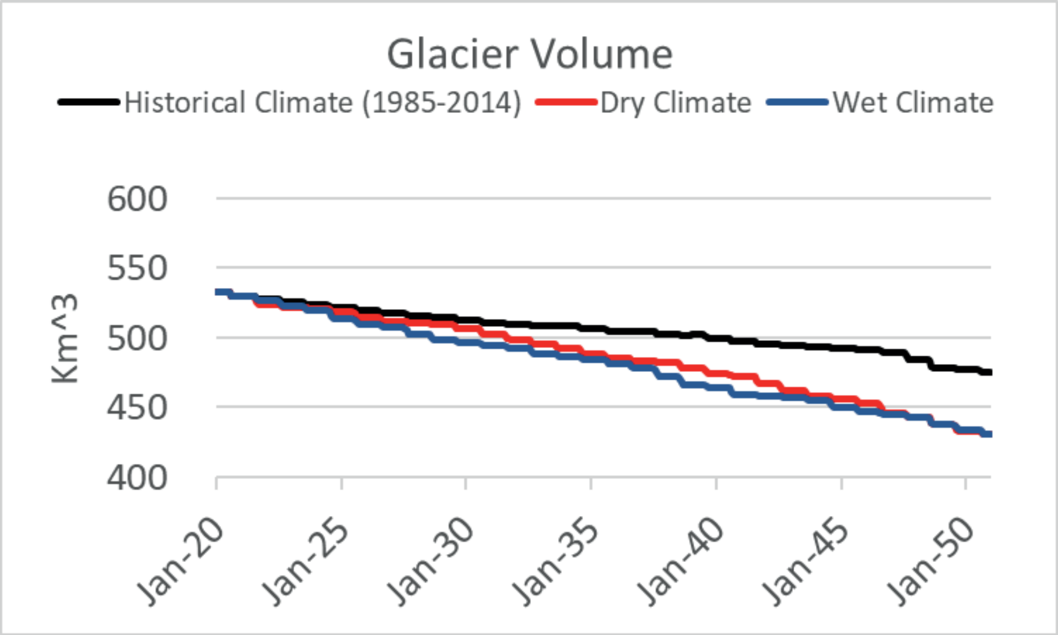


Figure 19. Change in glacier volume under different climate projections

The WEAP model results for the Vakhsh river flows into the Nurek reservoir, which reflect natural conditions unaffected by upstream operations, reveal significant differences under historical, dry, and wet climate sequences. Annual flows are expected to decrease by about 15 percent under the Dry climate projection relative to the historical sequence, while the Wet climate projection is projected to increase annual flows by approximately 10 percent compared to historical conditions (see Figure 20 below).

The monthly hydrographs show notable differences in seasonal patterns. Specifically, peak flows are significantly lower under the dry scenarios. In contrast, the wet climate projection features markedly higher baseflows during the dry season compared to both historical and dry climate projections, indicating a more sustained water supply throughout the year. These findings highlight the varying impacts of these projections on river flows, with significant implications for water resource management in the basin.

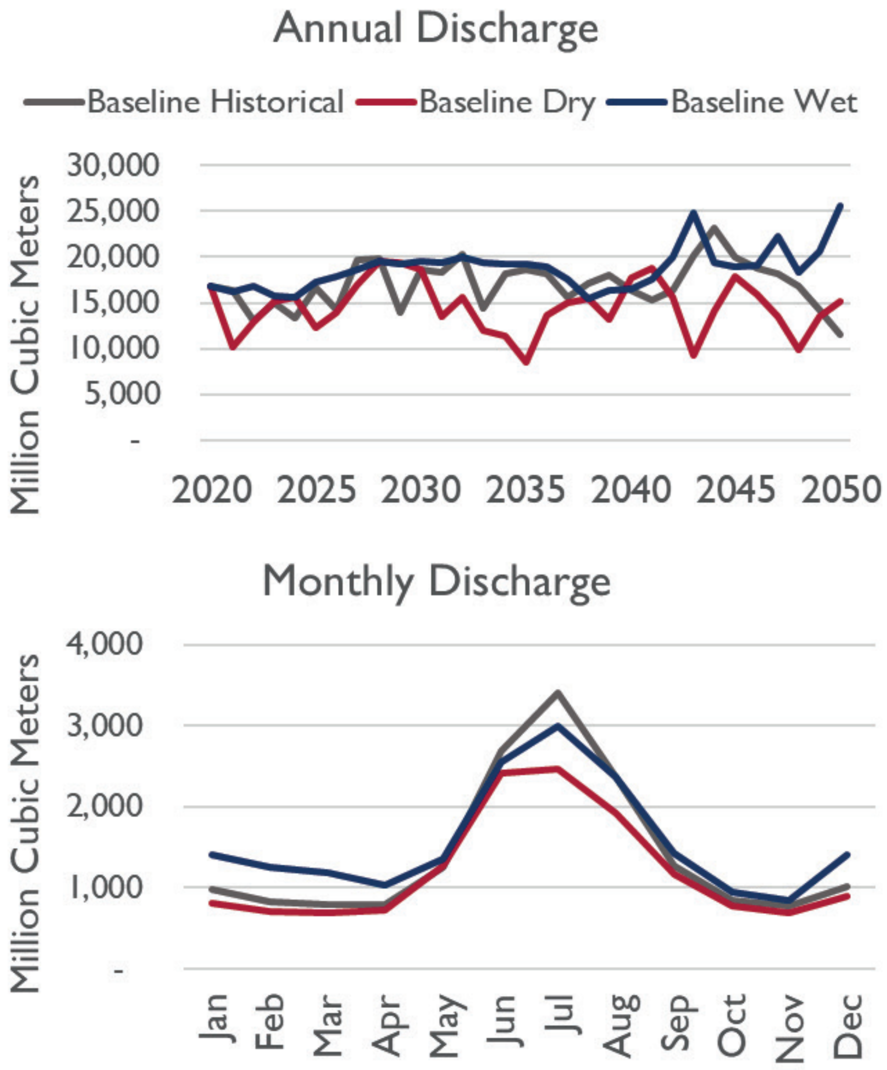


Figure 20. Vakhsh river flows above Nurek dam

The WEAP model estimates crop water requirements under historical, dry, and wet climate projections, highlighting the impact of temperature variations on agricultural water demand (Table 4 and Figure 21). Under the historical climate sequence, the average annual crop water requirement is 59.6 billion cubic meters per year. This value increases significantly under the dry climate projections, rising by 18 percent due to higher temperatures, which lead to increased evapotranspiration and greater water needs for crops. In contrast, the wet climate projection results in a more modest increase of 2 percent in crop water requirements, also driven by rising temperatures but mitigated by higher precipitation levels. These estimates underscore the sensitivity of agricultural water demand to varying climate projections, particularly under hotter and drier conditions.

Table 4. Impacts of varying climate projections on crop water requirements

	Average Annual Water Demand (2030-2050)	
	Million cubic meters	Percent increase over Historical
Historical	59,600	
Dry	70,648	18%
Wet	60,972	2%

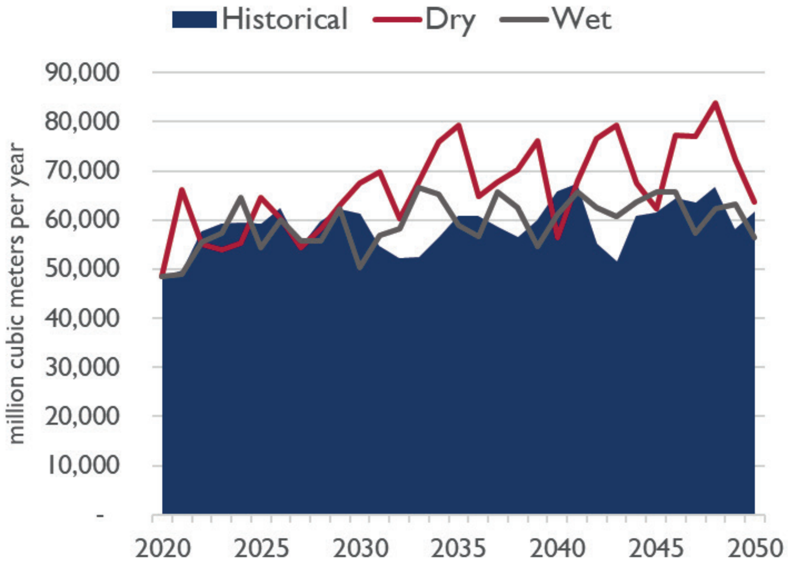


Figure 21. Impacts of varying climate projections on crop water requirements

Integrated modeling results under Baseline pathway

This section presents the results for the Baseline scenario (S1), where the WEAP model has been linked to the LEAP model. This integrated approach provides insights into the interactions between water resource management and energy production in the Amu Darya basin.

The reservoir storage results for the Baseline scenario (S1) under historical, dry, and wet climate projections show notable differences in water storage levels (Figure 22). In the early part of the simulation, before the storage expansion, each climate projection shows that storage levels regularly return to full capacity. Initially, total reservoir storage in the Amu Darya basin is just over 24,000 million cubic meters. This capacity increases to 37,500 million cubic meters with the addition of the Rogun hydropower plant in the latter part of the simulation. Following Rogun's introduction, both the wet and historical climate projections run estimate that average total storage remains at about 80 percent of the total capacity. In contrast, the dry climate projection struggles to maintain reservoir levels, with average total storage around 50 percent of the total capacity.

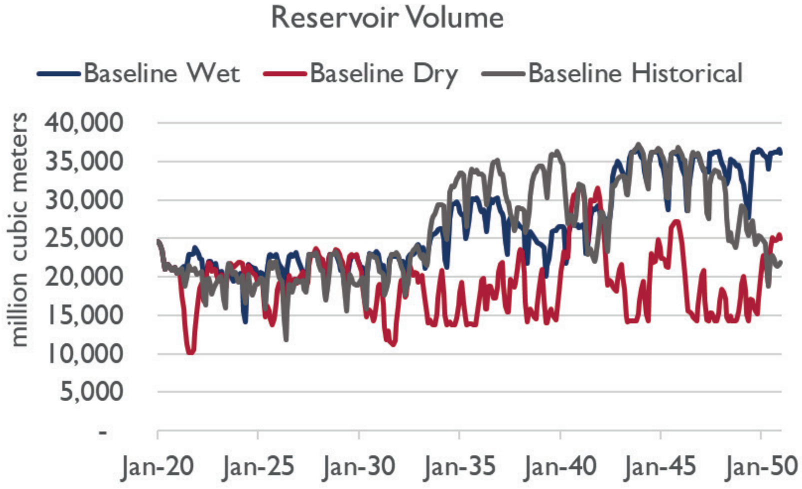


Figure 22 Total storage volume for reservoirs within the Amu Darya river basin.

Figure 23 illustrates the annual hydropower generation for the simulation period from 2020 to 2050. The results for the historical and wet climate projections show a general increase in hydropower production in the early 2030s, coinciding with the expected commissioning of the Rogun hydropower plant. This new facility is anticipated to boost the overall hydropower capacity by 12 percent. Following the introduction of Rogun, the inter-annual hydropower generation varies considerably across different climate projections. Compared to the historical climate projection, annual hydropower generation decreases by 28 percent under the Dry climate projection and increases by 5 percent under the Wet climate scenario. These variations underscore the substantial impact of varying climate projections on hydropower production in the basin.

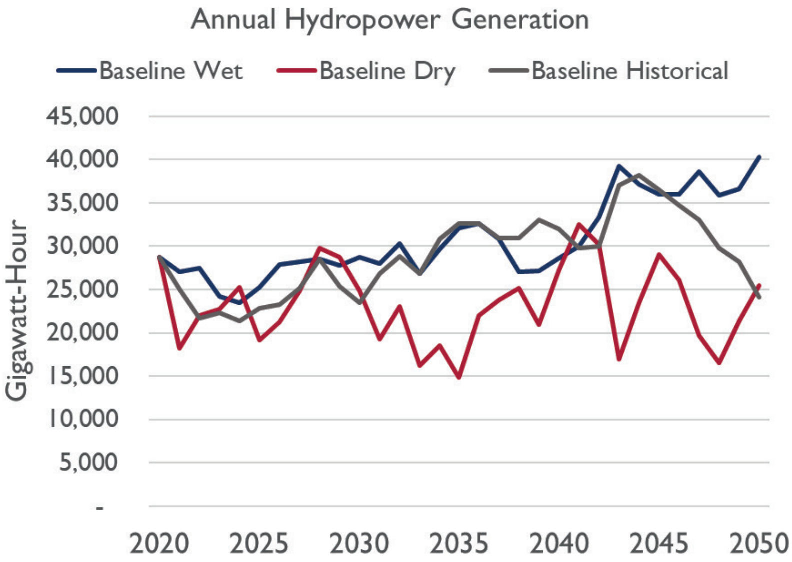


Figure 23. Annual hydropower generation within the Amu Darya river basin

The WEAP results for annual water deliveries for irrigated agriculture indicate that total annual river diversions for this purpose are similar under each climate projection for each basin country (Figure 24). In general, the higher temperatures associated with the dry and wet climate projections lead to higher crop water requirements and, consequently, increased river diversions to meet those demands, provided there is sufficient water available. Both Tajikistan and Turkmenistan are generally able to meet these increased water demands, resulting in their annual water deliveries increasing by about 3 percent under the dry climate projection and five percent under the wet climate projection. Uzbekistan, however, experiences different outcomes: while it sees the same increased deliveries under the wet climate projection, it faces a six percent decrease in water deliveries under the dry climate projection.

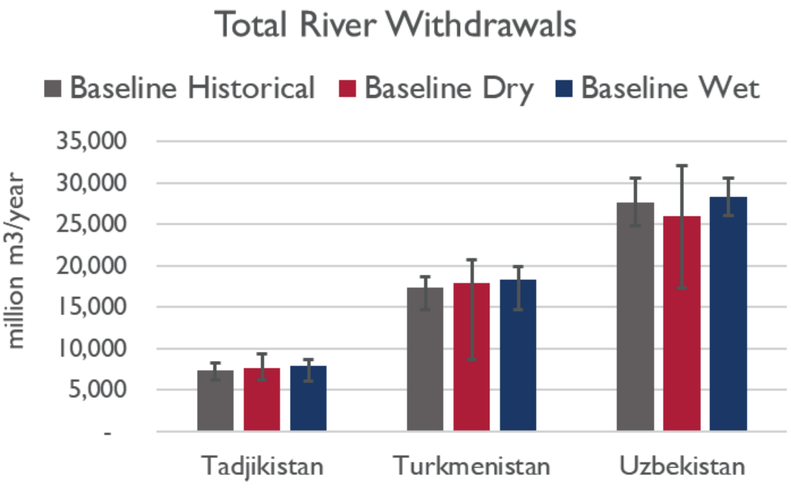


Figure 24. Total river withdrawals for irrigated agriculture by country

Figure 25 presents these same results with a higher level of granularity, showing total river diversions for each of the main canals considered in the WEAP model. These results indicate that most canals reflect the same pattern of deliveries observed at the national level, with slightly higher deliveries under both dry and wet climate projections. However, these results also highlight the specific canals in Uzbekistan that appear most vulnerable to reduced deliveries under the dry scenario—specifically, the main canals in the Zeravshan and Surkhandarya sub-basins. This granularity provides a clearer picture of how different parts of the basin may be differently impacted by climate projections, emphasizing the need for targeted water management strategies in these more vulnerable areas.

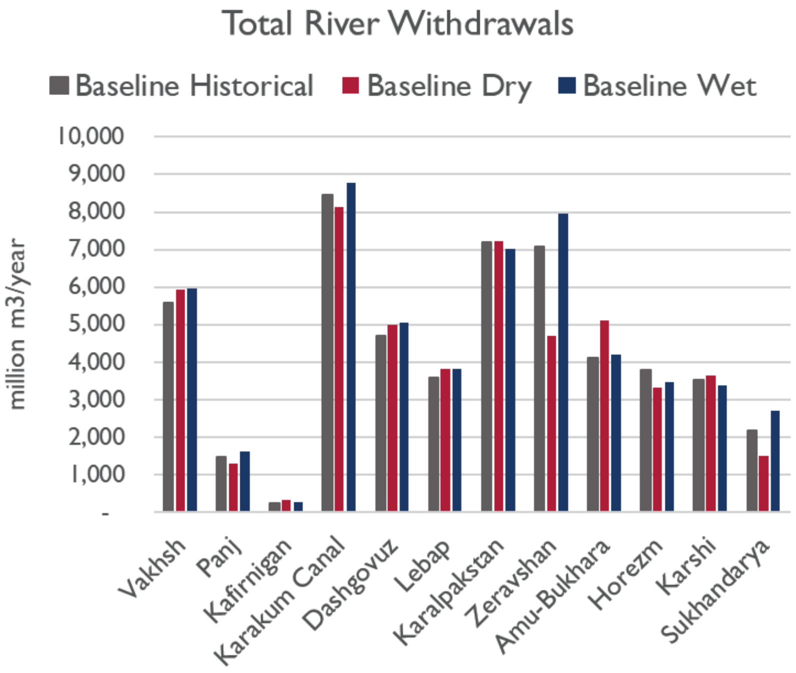


Figure 25 Total river withdrawals for irrigated agriculture by canal

Figure 26 shows total annual production for irrigated agriculture. These results indicate a consistent increase in production for each climate projection, primarily attributable to the modeling assumption of improving crop yields due to continued investments in farming practices. The wet climate projection shows an average 2 percent increase in production over the historical climate projection, which aligns with the higher water deliveries observed. Conversely, the dry climate projection exhibits a 15 percent decrease in production relative to the historical climate projection, despite total water deliveries being 3 percent higher. This suggests that the increased water deliveries under the dry climate projection were insufficient to meet the heightened crop water requirements, leading to a significant decline in agricultural productivity

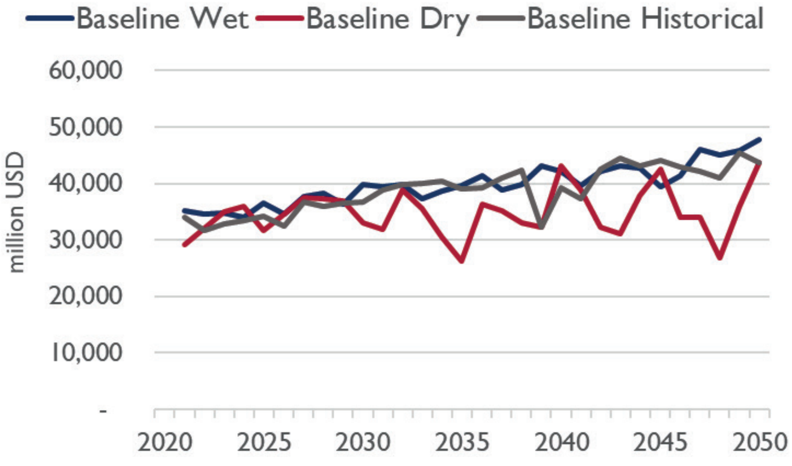


Figure 26. Total annual production of irrigated agriculture

Comparison of Baseline to WEAP only

This section presents the same set of WEAP model results as explored in the previous section. However, in this case, the WEAP model was run independently without linkage to LEAP. This analysis allows for a direct comparison of how water resource management and outcomes differ when energy planning considerations are not integrated into the simulation.

The following results reveal that the WEAP model results in standalone mode are very similar to the results when WEAP is integrated with LEAP. Unlike in the Syr Darya river basin, we see very little difference in the outcomes between the two modes in the Amu Darya basin. The primary reason for this similarity is the location of key hydropower dams relative to the basin's flows. In the Syr Darya basin, large hydropower facilities are situated on rivers that contribute significantly to the flows used for downstream irrigation. Consequently, the operation of these facilities to meet hydropower objectives has a direct impact on downstream irrigation. In contrast, flows along the lower Amu Darya river come from several large tributaries that are not as heavily dominated by hydropower operations. As a result, the integration of energy planning with water resource management has less impact on the WEAP model results in the Amu Darya basin.

The first set of model results for reservoir storage volume (Figure 27) and total hydropower generation (Figure 28) show that differences between the standalone and integrated model runs appear only under the dry climate projection. In this scenario, reservoir storage volume is occasionally drawn down more in the integrated model run compared to the standalone run. This results in modest reductions in hydropower generation, highlighting the minor but notable impact of integrating energy planning with water resource management under dry climate projection.

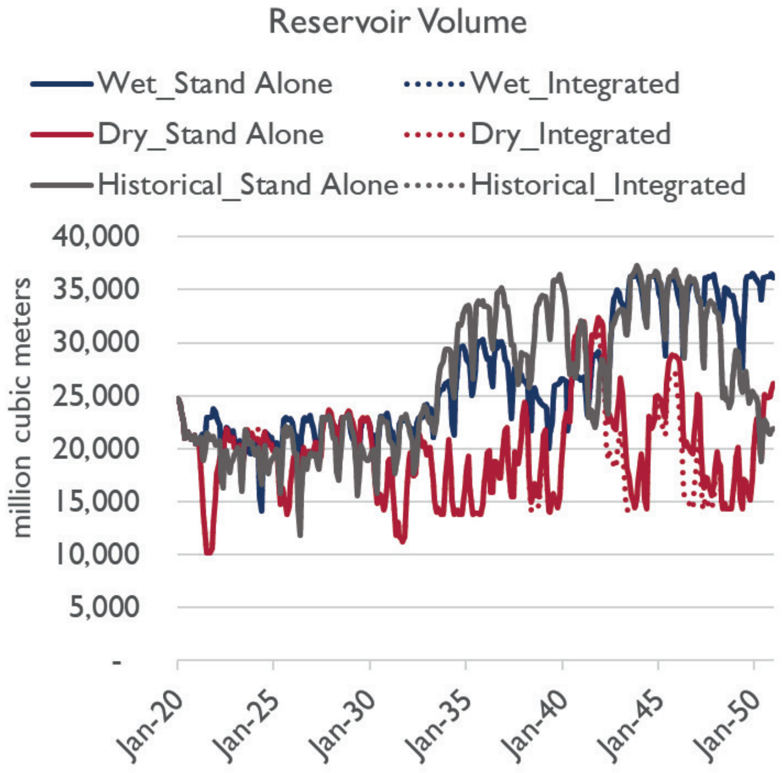


Figure 27. Comparison of reservoir storage volumes for the Baseline scenario (S1) run as standalone (WEAP-only) mode versus integrated (WEAP and LEAP) mode.

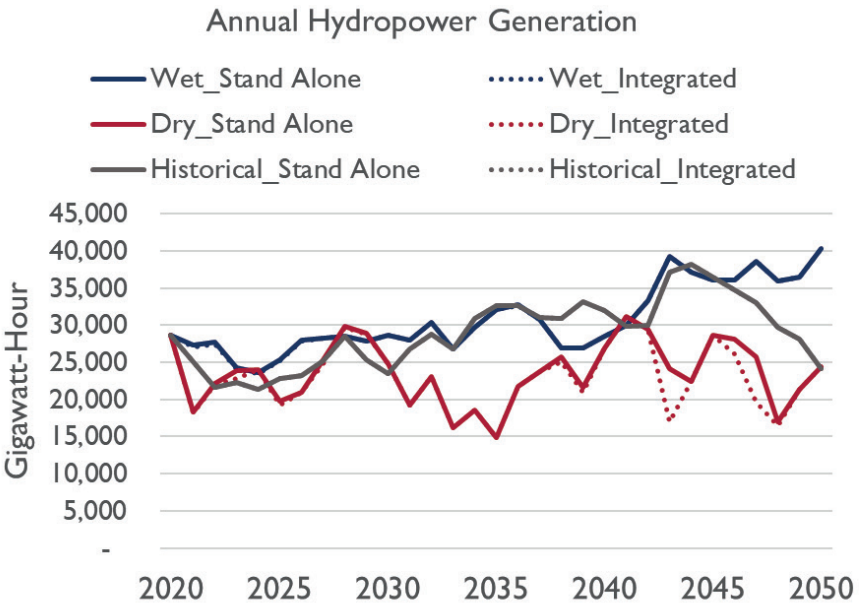


Figure 28. Comarison of annual hydropower generation for the Baseline scenario (S1) run as standalone (WEAP-only) mode versus integrated (WEAP and LEAP) mode

Figure 29 displays the total river withdrawals for irrigated agriculture under the baseline (S1) run in standalone mode. These data are virtually identical to the results previously observed when WEAP was run in tandem with LEAP (Figure 30). This consistency indicates that the integration of energy planning does not significantly alter water withdrawals for agriculture in the Amu Darya basin. The similarities in the results between the standalone and integrated runs further emphasize that the primary factors driving agricultural water demand and allocation remain unchanged, regardless of the energy planning considerations.

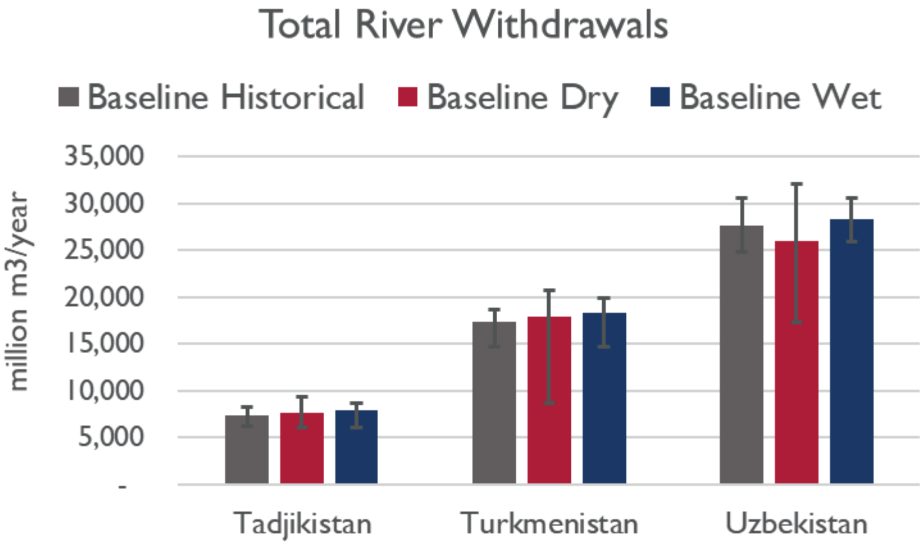


Figure 29. Total river withdrawals for irrigated agriculture by country (WEAP standalone run)

Figure 30 shows the production from irrigated agriculture under the same baseline (S1) in standalone mode. Once again, the standalone model generated results that were nearly identical to the integrated model runs. This suggests that agricultural productivity, like water withdrawals, is not significantly impacted by the integration of energy and water resource management in the Amu Darya basin. These findings highlight that, in this particular basin, the critical determinants of agricultural water use and production are largely independent of the hydropower generation strategies explored in the integrated WEAP-LEAP model.

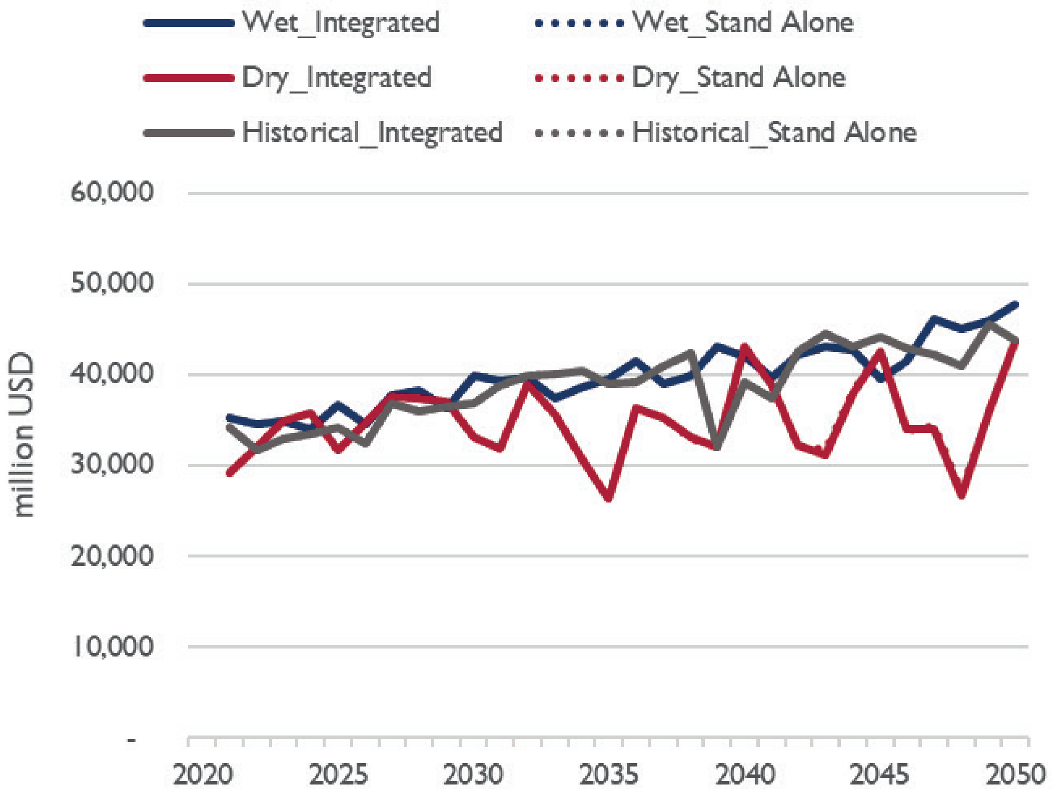


Figure 30. Comparison of total annual production from irrigated agriculture for the Baseline scenario run as standalone (WEAP-only) mode versus integrated (WEAP and LEAP) mode

Agricultural efficiency (integrated modeling results)

The following section discusses the results from the integrated WEAP-LEAP model runs for a scenario in which adaptation measures are focused on improving efficiency within irrigated agriculture. These efficiency measures target the reduction of canal losses and the enhancement of on-field irrigation efficiency. By analyzing the impact of these interventions, we aim to understand how increased agricultural efficiency can influence water resource management and hydropower generation in the Amu Darya basin under varying climate projections.

The implementation of agricultural efficiency measures plays a crucial role in reducing the overall water demand for irrigated agriculture. By targeting the reduction of canal losses and enhancing on-field irrigation efficiency, these measures significantly decrease the amount of water required to sustain agricultural activities. Specifically, under the historical climate projection, these improvements lead to a 13 percent reduction in average annual water demands (Table 5 and Figure 31). This reduction is achieved by minimizing water wastage during distribution and ensuring that a greater proportion of the diverted water reaches the crops effectively.

Table 5. Change in irrigation water demands with Agricultural Efficiency scenario(S2)

	Average Annual Water Demand (2030-2050)	
	million cubic meters	Percent Change
Baseline	65,227	
Agricultural Efficiency	56,510	-13%

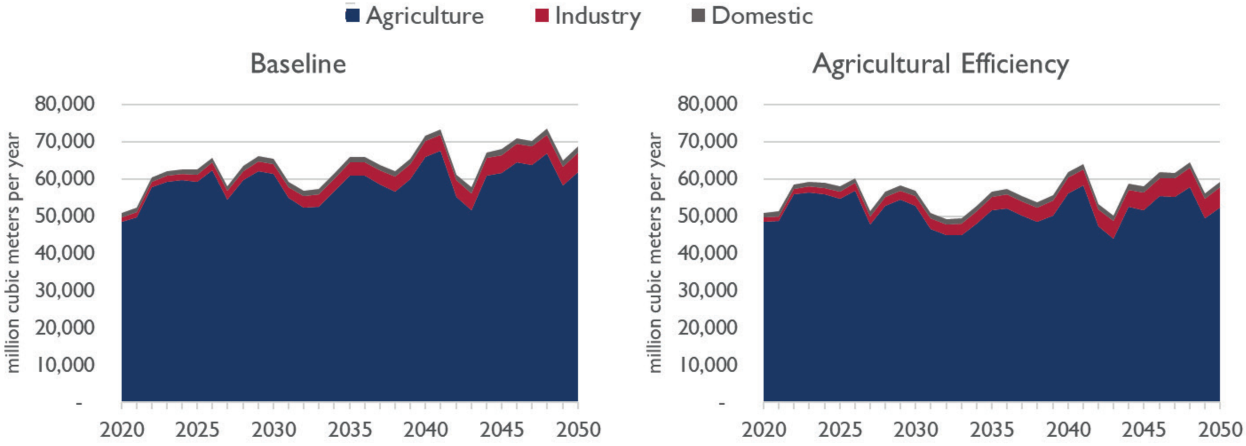


Figure 31. Change in irrigation water demand with Agricultural Efficiency scenario (S2)

The WEAP results for the Agricultural Efficiency scenario (S2), compared to the Baseline scenario(S1), show no differences in reservoir storage or hydropower generation across the three climate projections—historical, dry, and wet (Figure 32 and Figure 33). Despite the implementation of measures to reduce canal losses and improve on-field irrigation efficiency, the overall storage levels in reservoirs and the amount of hydropower generated remain unchanged. This suggests that the efficiency measures primarily benefit agricultural water use without significantly impacting the broader hydrological system or energy production within the basin. Consequently, while these measures are effective in reducing agricultural water demand, they do not alter the overall water availability or hydropower generation capacity in the Amu Darya basin under varying climate projections.

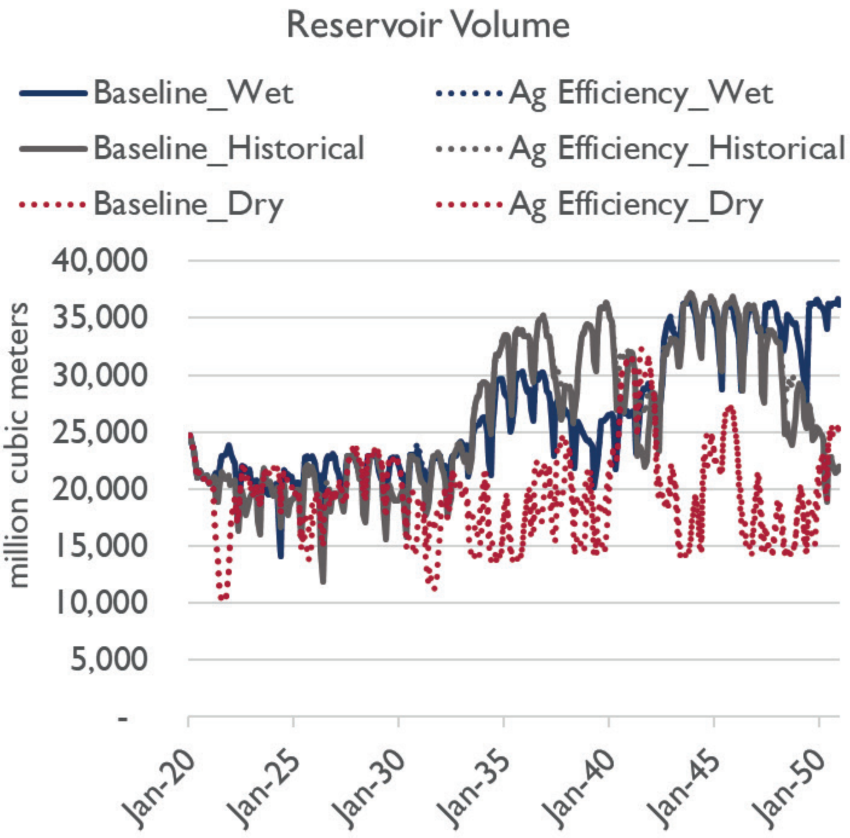


Figure 32. Comparison of reservoir storage volumes under Baseline(S1)and Agriculture Efficiency (S2)

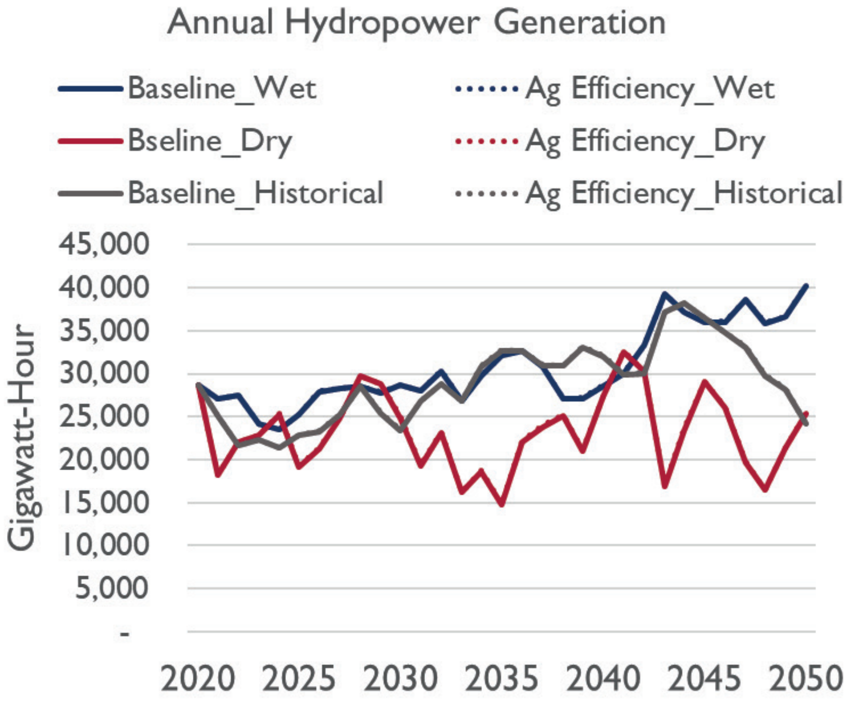


Figure 33. Comparison of annual hydropower generation under Baseline(S1)and Agriculture Efficiency (S2)

Comparing river diversions to agriculture between the Baseline scenario (S1) and the Agriculture Efficiency scenario (S2) under the three climate projections reveals a consistent impact across all climate projections (Figure 34). In the Agriculture Efficiency scenario (S2), total annual water deliveries to agriculture in Tajikistan are reduced by 7 percent under each climate projection-historical, dry, and wet. Similarly, water deliveries in Turkmenistan see a 20 percent reduction under each climate projection, while Uzbekistan experiences a 6 percent reduction in water deliveries under each scenario. These reductions indicate that the efficiency measures, such as reducing canal losses and improving on-field irrigation practices, lead to significant water savings for agricultural purposes regardless of the climate projection, thereby enhancing water use efficiency across the basin.

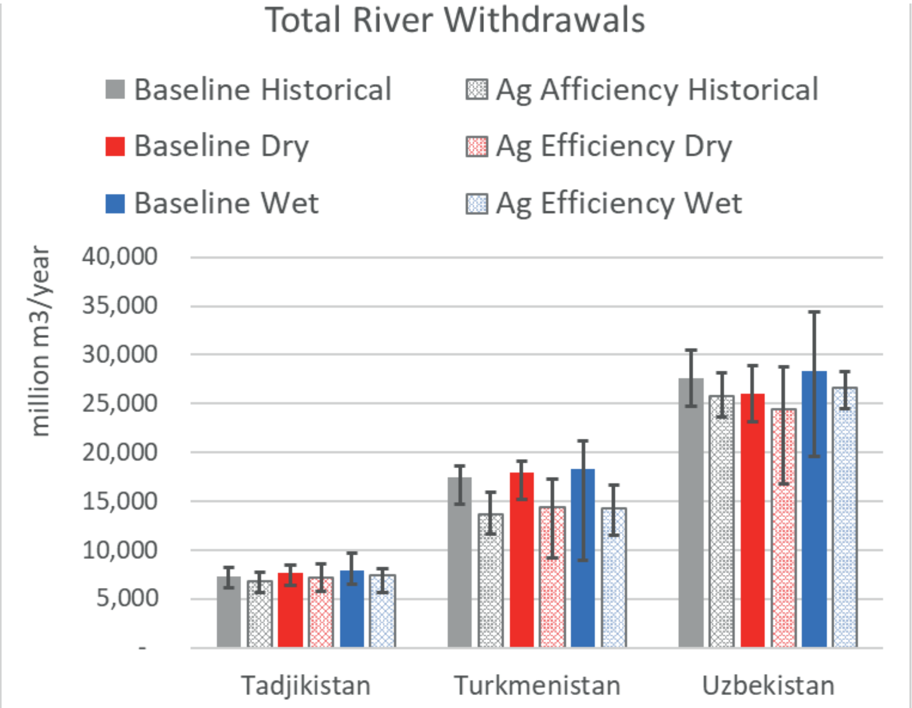


Figure 34. Comparison of river diversions for agriculture under Baseline(S1)and Agriculture Efficiency (S2)

The WEAP results for the production of irrigated agriculture under the Baseline (S1) and Agriculture Efficiency (S2) scenarios demonstrate a notable improvement in agricultural outcomes with increased efficiency (Figure 35). Under the Agriculture Efficiency scenario (S2), total agricultural production increases across all climate projections—historical, dry, and wet—despite a 12 percent reduction in overall river diversions to agriculture. This reduction in water use, coupled with an 18 percent increase in agricultural production, indicates a significant improvement in water productivity. These findings highlight the effectiveness of implementing efficiency measures, such as reducing canal losses and enhancing on-field irrigation practices, in maximizing agricultural yield while minimizing water consumption, thereby promoting sustainable water resource management in the basin.

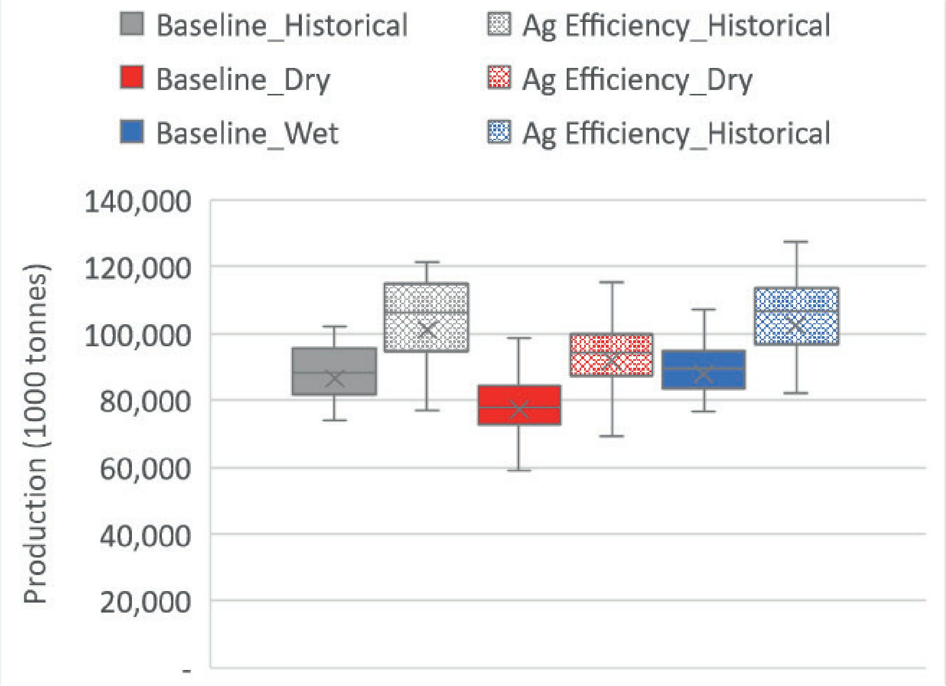


Figure 35. Comparison of annual agricultural production under Baseline(S1)and Agriculture Efficiency (S2)

Cooperation

The following section discusses the results from the integrated WEAP-LEAP model runs for a scenario in which irrigated agriculture is assigned a higher priority than hydropower generation. This scenario (S4) represents a significant shift in water allocation priorities, aiming to ensure that agricultural water needs are met before allocating water for hydropower production. By examining the outcomes of this prioritization, we seek to understand its impact on water resource distribution, agricultural productivity, and hydropower generation within the Amu Darya basin under various climate projections.

Comparing the Baseline scenario (S1) in WEAP to the Cooperation scenario (S4) reveals significant differences in average reservoir volumes across different climate projections following the expansion of storage with the addition of Rogun (Figure 36). Relative to the Baseline scenario (S1), average reservoir volumes increase from 80 to 90 percent with cooperation under the wet climate projection, and from 50 to 60 percent with cooperation in the dry climate projection. These results indicate that the Cooperation scenario (S4), which prioritizes water deliveries to irrigated agriculture over hydropower production, leads to improved reservoir storage levels across all climate projections, highlighting its potential for enhancing water security and resilience in the Amu Darya basin.

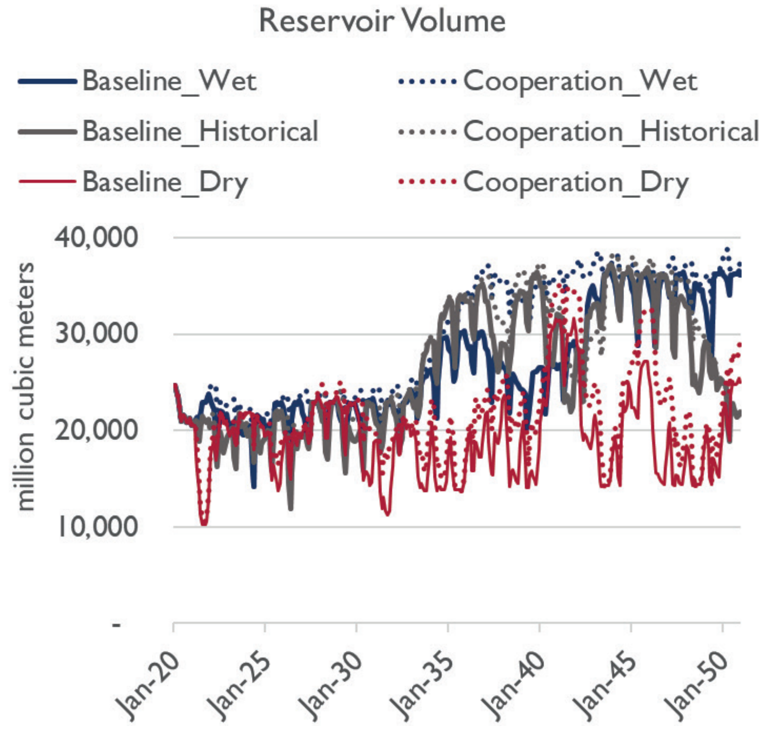


Figure 36. Comparison of reservoir storage volumes under Baseline (S1) and Cooperation (S4) scenarios

The results comparing hydropower generation between the Cooperation scenario (S4) and the Baseline scenario (S1) highlight varying outcomes across different climate projections (Figure 37). Under the Cooperation scenario (S4), hydropower generation experiences a slight decrease of 1 percent under the historical climate projection. Conversely, in the Wet scenario, hydropower generation increases by 2 percent, which is attributed to the higher heads maintained at the dams. However, under the Dry climate projection, hydropower generation sees a notable decrease of 12 percent. This reduction is primarily due to fewer releases through the turbines as water resources are prioritized for other uses, such as maintaining higher reservoir levels for irrigation during periods of lower precipitation. These findings underscore the trade-offs involved in water allocation decisions and emphasize the importance of adaptive management strategies to optimize hydropower production while meeting the diverse water needs of the Amu Darya basin under varying climate projections.

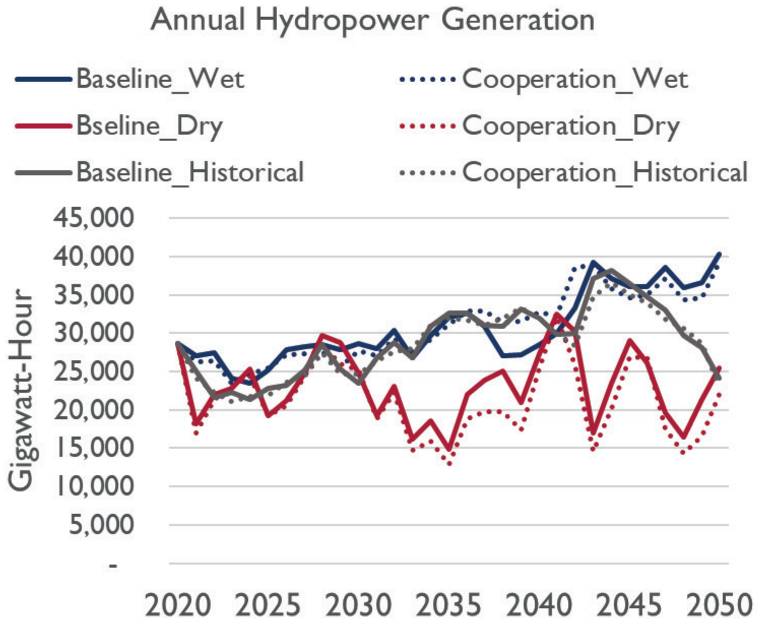


Figure 37 Comparison of annual hydropower generation Baseline (S1) and Cooperation (S4) scenarios

The results for water deliveries to agriculture under the Cooperation scenario (S4) relative to the Baseline scenario (S1) show minimal differences (Figure 38) and are similar to those observed under the Agriculture Efficiency scenario (S2) (Figure 38). This similarity can be attributed to shared assumptions regarding the reduction of canal losses and improvements in irrigation efficiency across both scenarios. However, it also suggests that altering priorities under the Cooperation scenario (S4) had little impact on water allocations for agriculture. As noted earlier, this is likely due to the fact that hydropower plants in the Amu Darya basin do not regulate the majority of river flows. Consequently, while the Cooperation scenario (S4) prioritizes water for agricultural use over hydropower generation, the actual deliveries to agriculture remain largely unchanged, highlighting the limited influence of hydropower operations on basin-wide water allocations for irrigation.

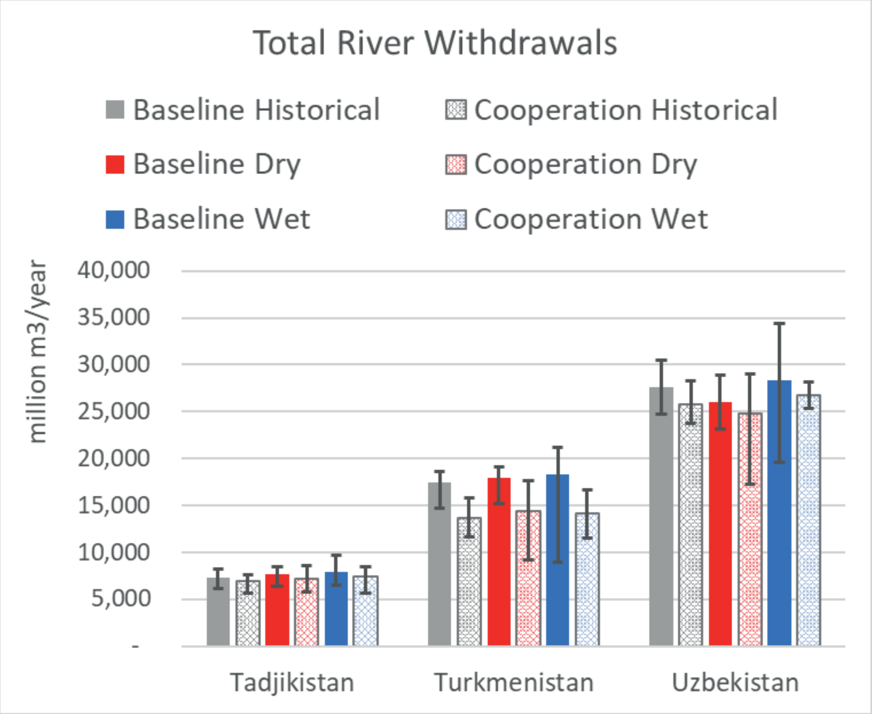


Figure 38. Comparison of river diversions for agriculture under Baseline (S1) and Cooperation (S4) scenarios

The results comparing annual production in irrigated agriculture between the Baseline (S1) and Cooperation (S4) scenarios (Figure 39) reveal striking similarities to those observed in the Agriculture Efficiency scenario (S2) (Figure 41). Across all climate projections, the Cooperation scenario (S4) shows significant improvements in agricultural production compared to the Baseline scenario (S1). Despite the shift in allocation priorities favoring irrigation over hydropower in the Cooperation scenario (S4), the outcomes for agricultural production remain virtually unchanged from those observed under the Agriculture Efficiency scenario (S2). This suggests that while the Cooperation scenario (S4) aims to prioritize water for agricultural use, the actual performance and productivity of irrigated agriculture are largely unaffected by this adjustment in water allocation strategies. These findings underscore the robustness of efficiency improvements in enhancing agricultural productivity, irrespective of changes in water allocation priorities within the Amu Darya basin.

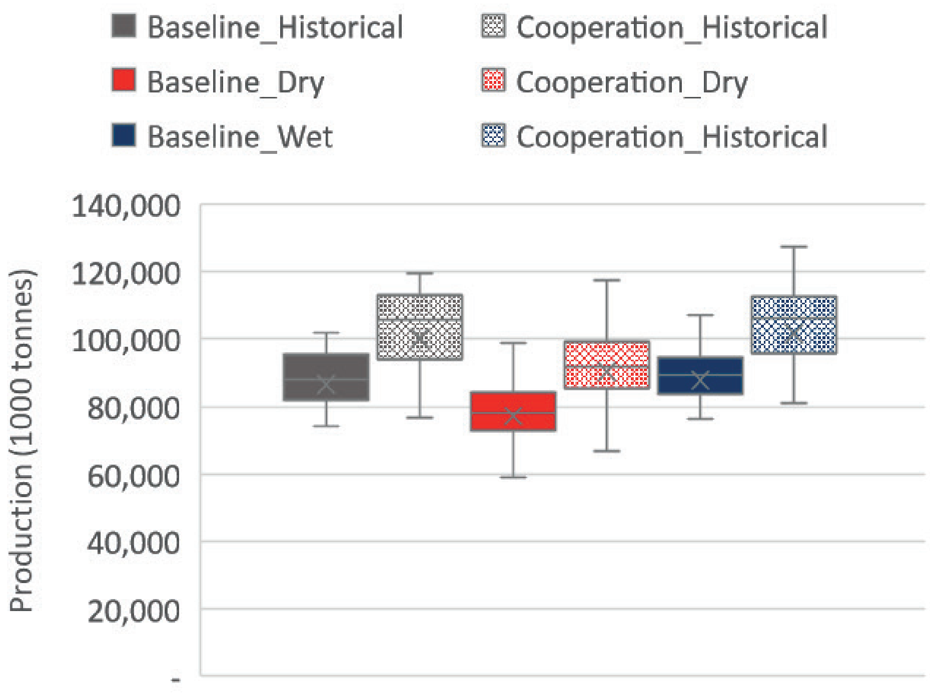


Figure 39 Comparison of annual agricultural production under Baseline (S1) and Agriculture Efficiency (S2) scenarios

Results with and without Qosh Tepa irrigation canal

The impacts of the Qosh Tepa irrigation canal are explored in detail in Case Study 1: Tuyamuyun Reservoir.

MACRO

Figure 40 shows the effect of the inclusion of the macroeconomic model in the model runs for the Kyrgyz Republic. For other riparian countries in the Amu Darya basin, GDP is exogenously specified and does not differ from one scenario to the next. As can be seen from the figures, due to the integration of LEAP, WEAP, and Macro, GDP can differ significantly from one scenario to the next. That is particularly true for the Cooperation scenario (S4). In that scenario, GDP is lower and more variable under both the wet and dry climate projections, with impacts stronger under the dry climate projection. In contrast, under improvements to water efficiency and agricultural output, GDP is higher and stable. Given the limited nature of the Cooperation (S4) scenario assumptions, this points to the need for further investigation of how Kyrgyz Republic could share the benefits of cooperation.

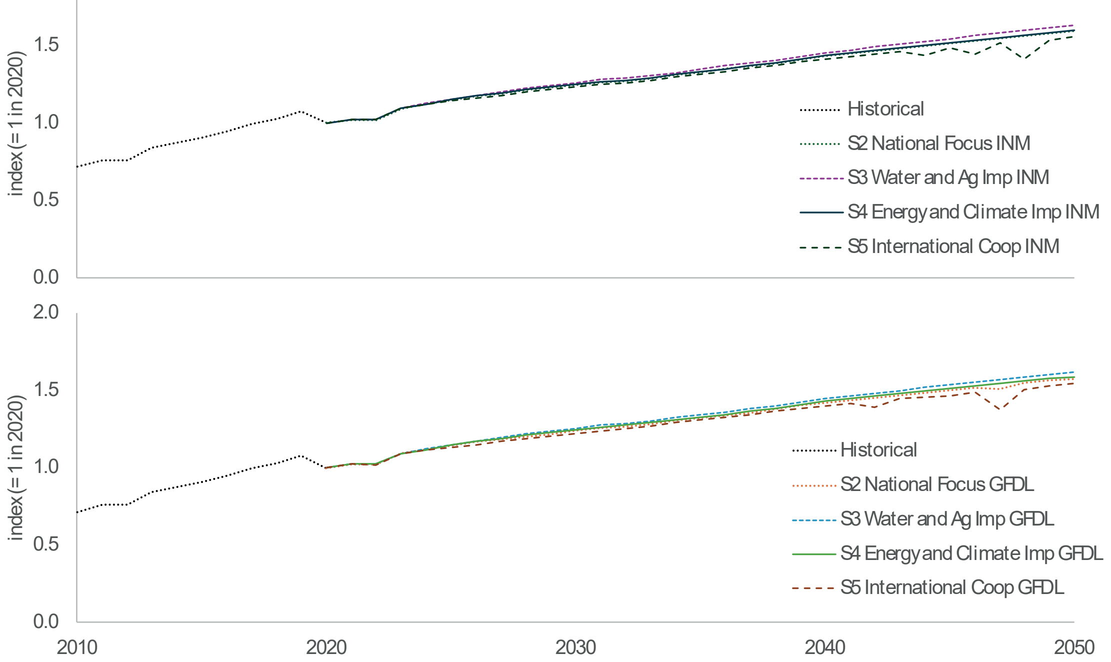


Figure 40: GDP for Kyrgyz Republic as an index normalized to a value of 1 in 2020: historical (from the World Bank World Development Indicators) and in scenarios (upper panel: dry climate projection; lower panel: wet climate projection)

Further details at sectoral level are shown in Figure 41 for industrial value added. As can be seen in the figure, trends broadly follow those for GDP. However, sectoral value added exhibits further volatility. That is to be expected for any subcomponent of GDP, as some fluctuations will cancel out between sectors. There are two sources of variability for the industrial sectors. First, a direct effect on water-constrained sectors, in which output is linked to WEAP's "coverage" indicator. Second, there are indirect effects: a demand effect through other sectors' demand for industrial output; and a supply effect due to reduced inputs from other water-constrained sectors, particularly agriculture.

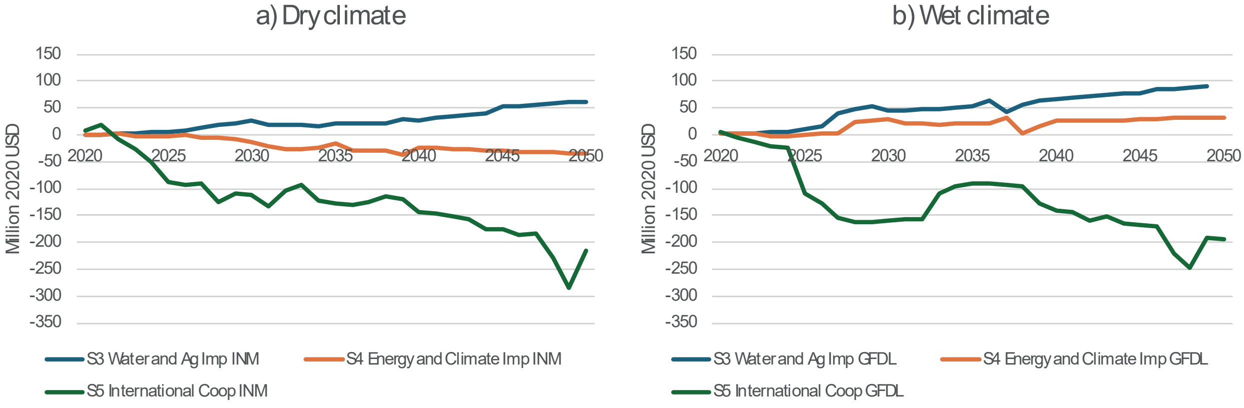


Figure 41: Industrial value added for Kyrgyz Republic, difference from the Baseline scenario (S1): a) dry climate projection; b) wet climate projection

CASE STUDY 1: TUYAMUYUN RESERVOIR

Description

The Tuyamuyun Hydro Complex (THC) is a significant water management facility located in the lower Amu Darya River. This extensive complex is strategically positioned to regulate river flow, provide water storage, and generate hydroelectric power. It plays a pivotal role in supporting agriculture, drinking water supply, and energy production. Importantly, the complex is physically located on the territory of Turkmenistan, while it is owned by and generates power and provides water for irrigation to Uzbekistan.

The complex consists of four main reservoirs—Channel, Kaparas, Sultansanjar, and Koshbulak—which have a combined storage capacity of 7.8 km³ (Figure 42). These reservoirs are designed to control the flow of the Amu Darya River, ensuring a reliable water supply during dry periods.

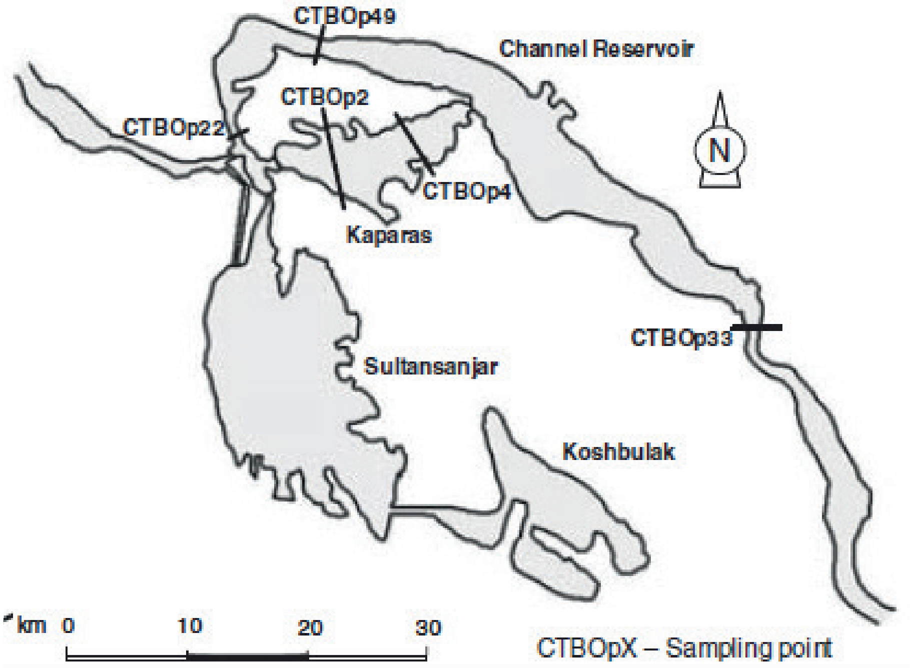
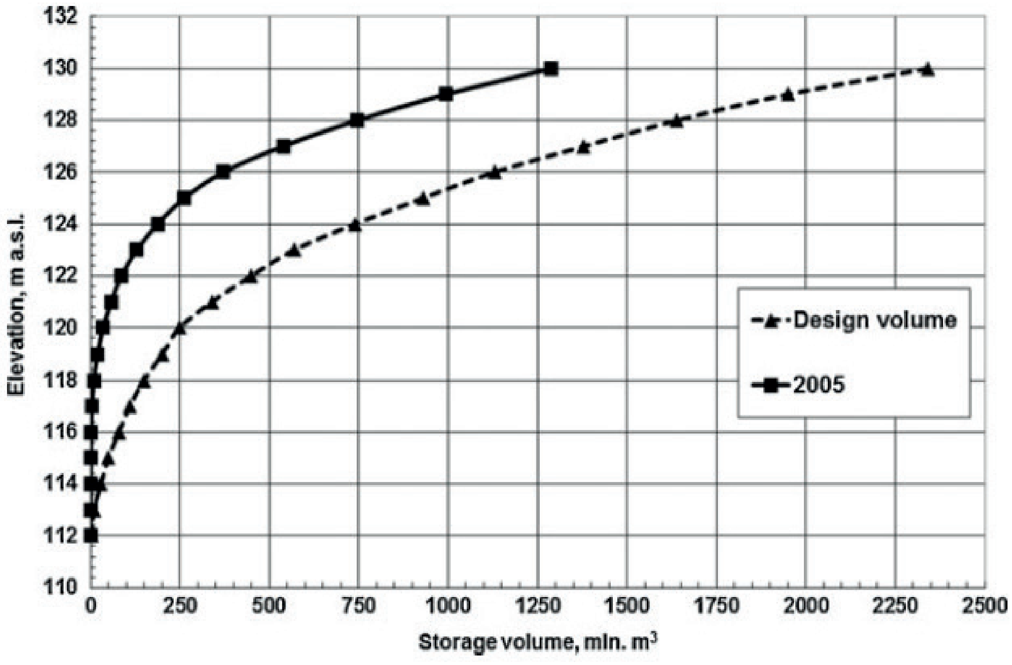


Figure 42. Configuration of Tuyamuyun Hydroengineering Complex (THC)

THC faces significant sedimentation issues, particularly in the Channel Reservoir (Figure 43). Sedimentation has reduced the storage capacity of the Channel Reservoir from its original 2.34 km³ to 1.287 km³. Currently, the average storage loss due to sedimentation is about 48 million cubic meters per year. If this rate continues, it is projected that the active storage within the Channel Reservoir will be lost to sedimentation by 2045. This loss of storage capacity poses a threat to the complex's ability to regulate water flow, provide reliable water supply, and mitigate flood risks.

Additionally, the Qosh Tepa Canal in Afghanistan presents a significant potential disruption to water management in the lower Amu Darya river basin. It is anticipated that annual diversions to the canal could reach a total between 10 and 16 billion cubic meters per year. This substantial diversion creates considerable uncertainty and concern for water use in the areas served by the THC. The potential reduction in water flow to the lower Amu Darya could adversely affect the complex's ability to provide a reliable water supply for irrigation, drinking water, and hydroelectric power generation. Moreover, it could exacerbate existing challenges related to sedimentation, further impacting the region's water resource management and agricultural productivity.



Volume elevation rating curves Channel Reservoir (THC), design 1981 and 2005

Figure 43. Design and current volume-elevation curves for Channel reservoir

Objectives

The objective of this case study is to utilize the WEAP model developed for the Amu Darya river basin to explore the potential impacts of the Qosh Tepa Canal on water management around THC and to examine water management strategies aimed at enhancing water security.

The study will assess how annual diversions of 13 billion cubic meters to the Qosh Tepa Canal in Afghanistan could disrupt water management in the lower Amu Darya region. It will evaluate the potential consequences for the THC, particularly concerning water supply reliability for irrigation and hydroelectric power generation.

Additionally, the study will explore water management strategies, including dredging sediments from the Channel Reservoir and expanding the overall storage capacity of THC. The potential benefits of these strategies to restore and maintain this reservoir function will be investigated. WEAP will be used to examine the effectiveness of these strategies to enhance water security in the face of reduced inflows caused by diversions to Qosh Tepa canal.

By modeling these scenarios with WEAP, the study aims to identify sustainable water management strategies that can ensure the long-term viability of the THC and secure water resources for the regions dependent on the Amu Darya river basin.

Methods

WEAP includes reservoir objects that model changes in water storage and managed releases for consumptive (domestic and irrigation) and non-consumptive (hydropower generation and ecosystem flows) water demands. These reservoir objects can be placed on rivers or off of rivers as off-stream storage.

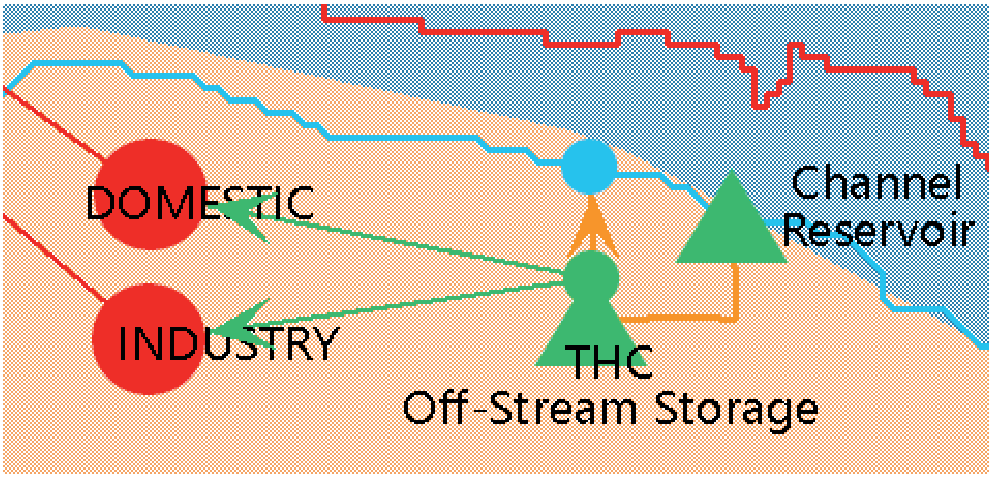


Figure 44. WEAP schematic representation of THC

Within WEAP, structured to reflect its physical layout and operational functions. It includes both in-stream and off-stream reservoirs (Figure 44). Within the model, the Channel reservoir, situated directly on the Amy Darya river, regulated river flow and primarily provides water for hydropower generation. Releases from this reservoir are specifically allocated for hydropower purposes. Off-stream, the Kaparas, Sultansuanjar, and Koshbulak reservoirs store water for irrigation and domestic water needs. There reservoirs manage water deliveries for consumptive uses, ensuring adequate supply for agriculture and urban areas.

This division enables WEAP to simulate the intricate water management dynamics within the THC accurately. It facilitates the evaluation of various scenarios, including the impacts of external factors like the Qosh Tepa Canal, and the effectiveness of strategies such as sediment dredging and reservoir expansion in enhancing water security and sustainability in the Amu Darya river basin.

Scenarios

In the WEAP model, several scenarios are explored to assess their impacts on water management in the Amu Darya river basin. These are summarized in Figure 45. The Baseline Scenario represents the current operational regime of the THC, serving as a reference without any changes.

Two management scenarios are considered to enhance THC performance. The Expand THC Storage scenario involves increasing the total reservoir capacity by 1000 million cubic meters (1 km^3), which is stated in the National Strategy "Uzbekistan 2030", adopted by the Government in 2023. This scenario evaluates the potential benefits of expanded off-stream storage across Kaparas, Sultansanjar, and Koshbulak reservoirs. It aims to enhance water security, mitigate risks from reduced inflows, and support sustainable water management practices.

The THC Dredge Scenario focuses on dredging sediments from the Channel Reservoir to restore its original storage profile. Sedimentation has reduced the Channel Reservoir's capacity, impacting its ability to regulate river flows and provide water for hydropower generation. This scenario examines improvements in water supply reliability, hydropower generation efficiency, and overall operational effectiveness.

Each scenario is also assessed under conditions with annual diversions of 13 billion cubic meters to the Qosh Tepa Canal in Afghanistan. These assessments explore how diversions to the Qosh Tepa Canal could affect water availability, reservoir operations, and the THC's capacity to meet demands for irrigation, domestic use, and hydropower downstream.

Through these simulations in WEAP, the model aims to provide insights into optimal water management strategies for the Amu Darya river basin. It considers climate variability, sedimentation rates, infrastructure changes, and policy interventions to support sustainable water resource management and enhance resilience in facing future challenges.

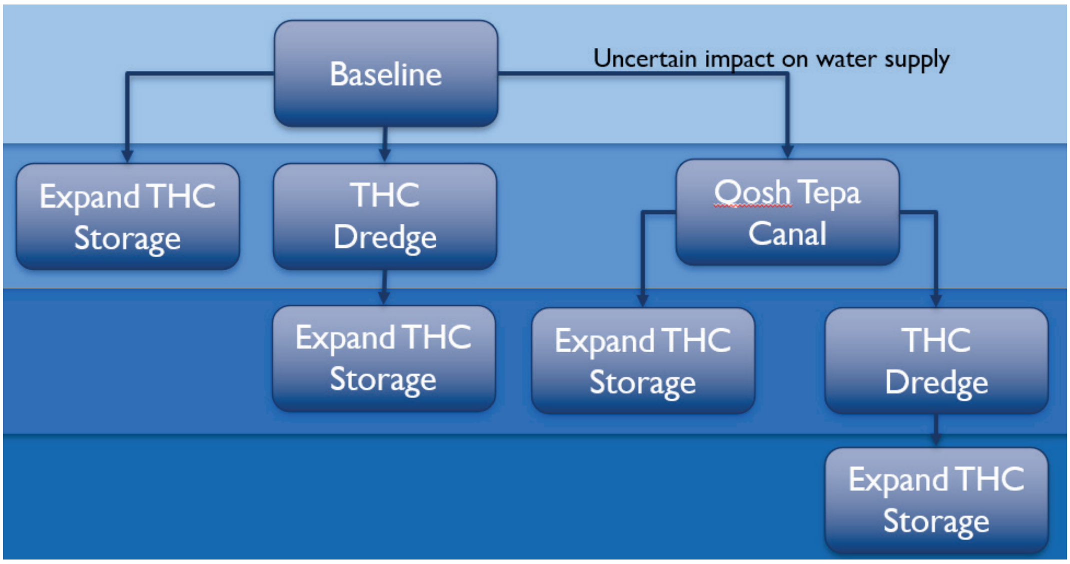


Figure 45. Scenarios evaluated in WEAP

Results

This section presents an analysis of key metrics across multiple scenarios simulated within the WEAP model for THC in the Amu Darya river basin. This section focuses on evaluating reservoir inflows, storage volumes, water deliveries from the THC for irrigation, and hydropower generation outputs. Each scenario—Baseline, Expanded Storage, and THC Dredge—is examined to understand their respective impacts on water resource management. Additionally, variations in these metrics are explored under conditions with and without diversions to the Qosh Tepa Canal, providing insights into how external factors influence water availability and operational efficiency of the THC.

Inflows

In the Baseline scenario evaluated within the WEAP model, the inflows into THC are analyzed both with and without diversions to the Qosh Tepa Canal. The results reveal significant differences: without Qosh Tepa diversions, the average annual inflow to THC amounts to 37,960 million cubic meters per year (Table 6 and Figure 46). However, with Qosh Tepa Canal diversions incorporated, this average decreases notably to 28,606 million cubic meters per year. This reduction signifies an average decrease of approximately 25 percent in total annual inflows, underscoring the considerable impact of external diversions on water availability and management within the basin.

Table 6. Average annual inflows into Channel reservoir with and without Qosh Tepa canal

Scenario	Average Annual Inflow (mln m^3)	Percent Change
Baseline	37,960	
Baseline with Qosh Tepa	28,606	-25%

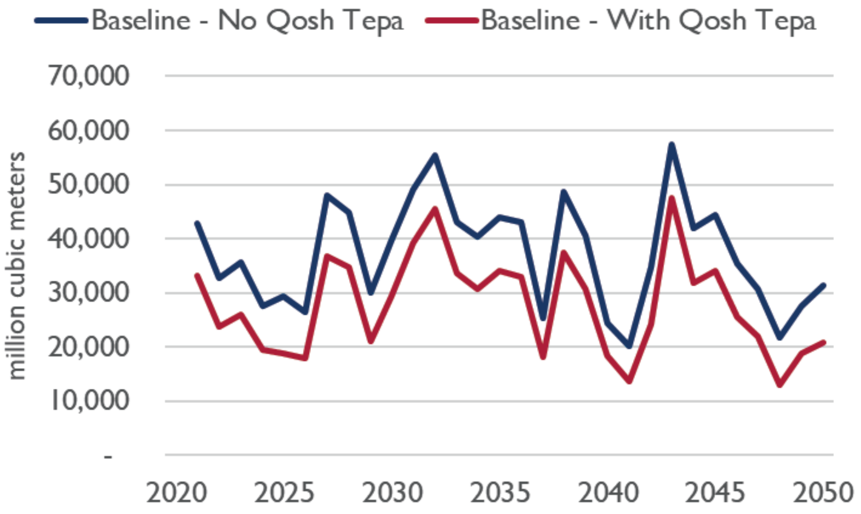


Figure 46. Average annual inflows into Channel reservoir for Baseline scenario with and without Qosh Tepa canal

Storage volume

The WEAP model results for total reservoir storage in the THC from 2020 to 2050 highlight distinct trends and impacts across different scenarios. In the Baseline scenario, depicted on the left of Figure 6, reservoir storage dynamics show a gradual decline in active storage due to sedimentation, which increases the level of inactive storage over time. This reduction in active storage results in frequent drawdowns that often reach inactive storage levels. The introduction of Qosh Tepa Canal diversions exacerbates these drawdowns, although the THC generally refills its reservoirs in most years.

Conversely, in the THC Dredging scenario depicted on the right of Figure 51, there is notably more usable storage capacity due to ongoing dredging efforts aimed at restoring the Channel Reservoir's original storage profile. Despite this improvement, similar patterns of drawdown and refilling are observed, albeit with a higher level of usable storage available. The addition of Qosh Tepa Canal diversions continues to amplify the extent of storage drawdowns, underscoring the heightened challenges posed by external water diversions on THC's storage dynamics and overall water management strategies.

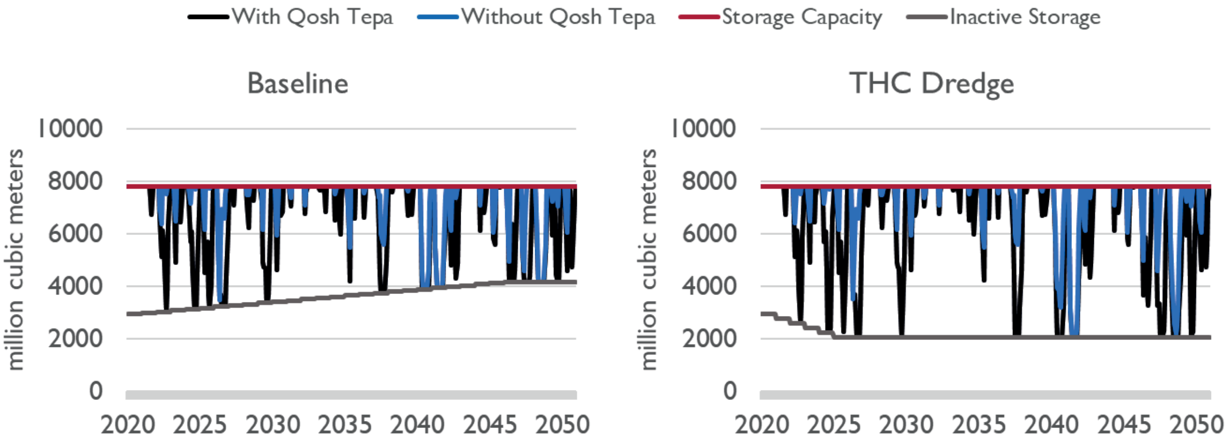


Figure 47. Total THC storage for Baseline and THC Dredge scenarios with and without Qosh Tepa canal diversions

The next set of results focuses on the storage levels within the THC, comparing two scenarios: Expanded Storage and Expanded Storage with Dredging. These results are displayed similarly to Figure 47, with Expanded Storage on the left and Expanded Storage with Dredging on the right (Figure 48).

In the Expanded Storage scenario (left side of Figure 48), the THC's reservoir storage volumes show a pattern similar to the Baseline scenario. Despite the increase in active storage capacity due to the expansion of THC's reservoir capacity, storage levels continue to fluctuate between full capacity and inactive storage. The larger active storage capacity allows for more water to be stored during peak inflow periods, but the frequency of drawing down storage to inactive levels and subsequent refilling remains consistent.

In contrast, the Expanded Storage with Dredging scenario (right side of Figure 48) shows slightly improved dynamics compared to the Expanded Storage scenario alone. With ongoing dredging activities aimed at maintaining reservoir efficiency and mitigating sedimentation, there is a higher availability of usable storage capacity. However, similar to other scenarios, the pattern of storage oscillation persists, indicating that despite expanded capacities and dredging efforts, the THC still faces challenges in maintaining consistent water storage levels.

These results underscore the complex nature of reservoir management in the THC, highlighting the importance of strategic planning, sediment management, and operational practices in ensuring sustainable water supply and resilience against external factors like sedimentation and diversions into the Qosh Tepa Canal.

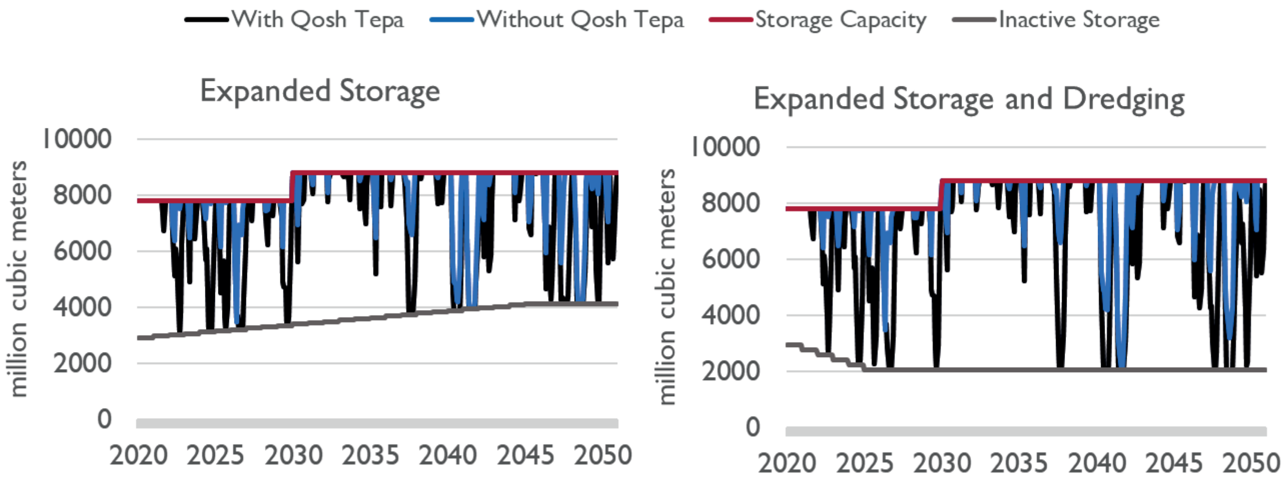


Figure 48. Total THC storage for Expanded Storage scenarios with and without dredging and Qosh Tepa canal diversions

Water deliveries

The WEAP model results for water deliveries to agriculture from the THC across various scenarios provide valuable insights into the impacts of different management strategies and external diversions from the Qosh Tepa Canal. Table 7 and Figure 49 illustrate annual water delivery data for the Baseline, Expanded Storage, and THC Dredging scenarios, both with and without Qosh Tepa diversions.

In the Baseline scenario, Qosh Tepa diversions have the most significant impact on water deliveries to agriculture, resulting in a reduction of annual deliveries by 6 percent compared to the baseline without diversions. This reduction underscores the substantial challenge posed by external water withdrawals on agricultural water availability within the basin.

Conversely, neither the Expanded Storage nor the THC Dredging scenarios show significant impacts on total water deliveries to agriculture when considered individually. These scenarios are primarily focused on enhancing reservoir capacities and managing sedimentation, which helps maintain consistent water supply levels for agricultural needs.

However, the combined effect of implementing both the Dredging and Expanded Storage scenarios proves beneficial in offsetting some of the negative impacts caused by Qosh Tepa diversions. Specifically, these strategies reduce the delivery reduction from 6 percent in the Baseline scenario to 4 percent in each individual scenario. When both strategies are implemented together, the reduction in water deliveries decreases further to only 3 percent compared to the Baseline, highlighting the synergistic benefits of implementing multiple water management strategies simultaneously.

Table 7. Average annual water deliveries from THC for selected scenario combinations.

Scenario	Annual Delivery (mln m³)	Percent Change from Baseline
Baseline	10,079	
Baseline with Qosh Tepa	9,467	-6%
Baseline with Dredging	10,119	0%
Baseline with Dredging and Qosh Tepa	9,721	-4%
THC Expansion	10,118	0%
THC Expansion with Qosh Tepa	9,646	-4%
THC Expansion with Dredging and Qosh Tepa	9,768	-3%

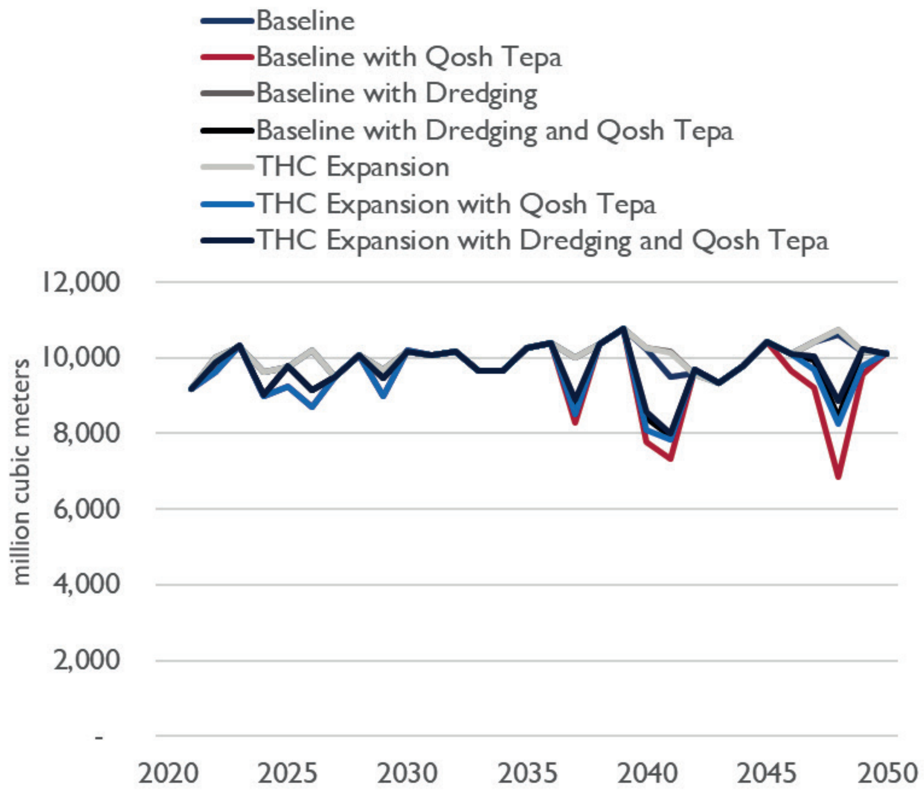


Figure 49 Annual water deliveries from THC for selected scenario combinations

Hydropower generation

The WEAP model results for hydropower generation from the Tuyamuyun Hydro Complex (THC) across various scenarios highlight the significant impacts of management strategies and external diversions from the Qosh Tepa Canal. These results, summarized in Table 8 and Figure 50, provide insights into how different scenarios affect THC's ability to generate hydropower.

In the Baseline scenario, Qosh Tepa Canal diversions threaten to reduce THC's hydropower generation by approximately 22 percent annually. This reduction underscores the substantial challenge posed by external water withdrawals on the complex's hydropower production capacity.

The interventions of Expanded Storage and Dredging scenarios individually show limited effectiveness in addressing this issue. Expanded Storage, aimed at increasing reservoir capacities, inadvertently diverts more water into off-stream portions of the THC, reducing the availability of water for hydropower generation and compounding the negative impact caused by Qosh Tepa diversions.

On the other hand, the Dredging scenario exhibits a modest effect, marginally increasing hydropower generation by 1 percent. Despite this improvement, it is insufficient to counterbalance the overall reduction caused by Qosh Tepa diversions.

Interestingly, when both strategies—Expanded Storage and Dredging—are combined, their impacts cancel each other out. While Expanded Storage exacerbates the diversion impact, dredging slightly offsets it. As a result, hydropower generation remains at approximately the same level as in the Baseline scenario with Qosh Tepa diversions, indicating that the combined strategies do not effectively mitigate the reduction in hydropower generation.

Table 8. Average annual hydropower generation for Baseline, Storage Expansion, and Dredging scenarios with Qosh Tepa canal diversions

Scenario	Average Annual Generation (GWH)	Percent Change from Baseline
Baseline	754	
Baseline with Qosh Tepa	587	-22%
Dredging with Qosh Tepa	598	-21%
THC Expansion with Qosh Tepa	576	-24%
Dredging and THC Expansion with Qosh Tepa	585	-22%

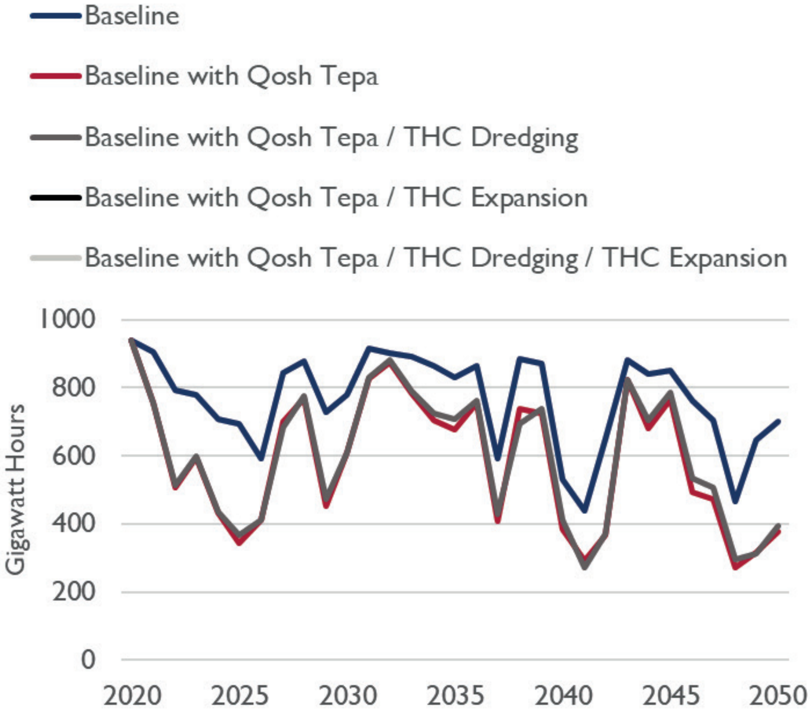


Figure 50. Annual hydropower generation for Baseline, Storage Expansion, and Dredging scenarios with Qosh Tepa canal diversions.

Conclusions and Recommendations

The findings from the WEAP model simulations of the Tuyamuyun Hydro Complex (THC) in the Amu Darya river basin reveal critical insights into water management strategies and their implications for sustainable resource utilization. Key conclusions drawn from the results are outlined below, accompanied by corresponding recommendations:

1. **Impact of Qosh Tepa Canal Diversions**: The simulations demonstrate that diversions into the Qosh Tepa Canal significantly impact both water deliveries to agriculture and hydropower generation from the THC. First, annual inflows into THC may be reduced by as much as 25 percent with diversions into Qosh Tepa. Annual water deliveries for agriculture are subsequently reduced by approximately 6 percent, highlighting the substantial challenge posed by external diversions on agricultural water availability. Similarly, hydropower generation faces a reduction of about 22 percent annually, underscoring the vulnerability of energy production to external water withdrawals.

   Recommendation: Implement policies and agreements that carefully manage and monitor water diversions into the Qosh Tepa Canal to mitigate adverse impacts on THC's water resources. Prioritize water allocation strategies that balance agricultural, domestic, and energy needs to maintain sustainable resource use.

2. **Effectiveness of Management Scenarios**: The Expanded Storage and THC Dredging scenarios, aimed at increasing reservoir capacity and mitigating sedimentation, show varying degrees of effectiveness. Expanded Storage, while increasing overall water storage, exacerbates water diversion impacts, reducing hydropower generation potential. Dredging efforts marginally increase hydropower generation by 1 percent but do not fully mitigate the broader impacts of Qosh Tepa diversions.

   Recommendation: Integrate dredging activities with expanded storage initiatives to maximize water storage efficiency while minimizing sedimentation impacts. Consider adaptive management strategies that dynamically adjust reservoir operations based on seasonal and annual water availability.

3. **Synergistic Approach**: Combining both Expanded Storage and Dredging strategies shows mixed results, with benefits in water delivery resilience but limited effectiveness in maintaining hydropower generation levels under Qosh Tepa diversions. The strategies offset each other, resulting in marginal improvements rather than substantial gains in resource sustainability.

   Recommendation: Explore hybrid approaches that integrate reservoir management strategies with advanced sediment control technologies. Invest in research and development to enhance sedimentation prediction and management capabilities to maintain reservoir functionality and optimize water use efficiency.

4. **Policy and Governance Enhancements**: Effective water management in the THC requires robust governance frameworks and policy interventions. Addressing legal and institutional gaps is crucial for coordinating water allocations, managing diversions, and implementing adaptive management strategies effectively.

   Recommendation: Strengthen institutional capacities and establish collaborative platforms for stakeholders across national and international boundaries to coordinate water management efforts. Foster dialogue and cooperation among riparian states to develop shared policies that promote equitable and sustainable water use practices.

In conclusion, sustainable water resource management in the Amu Darya river basin necessitates proactive measures to balance competing demands and mitigate external pressures. By implementing integrated strategies, enhancing governance frameworks, and prioritizing adaptive management approaches, stakeholders can enhance resilience, optimize resource use efficiency, and ensure long-term sustainability of water resources in the region.

CASE STUDY 2: ORTO-TOKOY (KASANSAY) RESERVOIR

Description

The Orto-Tokoy Reservoir, located on the Kasansay River in the countries of Kyrgyz Republic and Uzbekistan, serves as a crucial channel reservoir with seasonal regulation (Figure 51). Its primary function is to control the flow of the Kasansay River to enhance the water supply for agricultural lands in both countries. The main beneficiaries of this water resource are the irrigation systems of farms, which collectively irrigate 28,000 hectares of land—2,000 hectares in Kyrgyz Republic and 26,000 hectares in Uzbekistan.

From 2018 to 2022, the average volume of water available for irrigation was 275 million cubic meters, though the system was originally designed to distribute up to 393 million cubic meters. Of the available water, 8 percent is allocated to command areas in Kyrgyz Republic, while the remaining 92 percent serves command areas in Uzbekistan. This distribution underscores the reservoir's vital role in supporting regional agriculture and ensuring sustainable water management across national borders.

The Kasansay river exhibits a distinct pattern in its annual discharge. The average annual flow rate is 8.6 cubic meters per second. Discharges typically start increasing in April, peak during May and June, and then decline steadily from July through September. During the period from September to March, water flows remain relatively stable, fluctuating between 3 to 5 cubic meters per second (Figure 52).

About 80% of the annual flow occurs from April to August, with the majority (60%) occurring specifically in May and June. This indicates a pronounced seasonal variability in the river's discharge, with significant contributions to overall flow during the spring and early summer months.

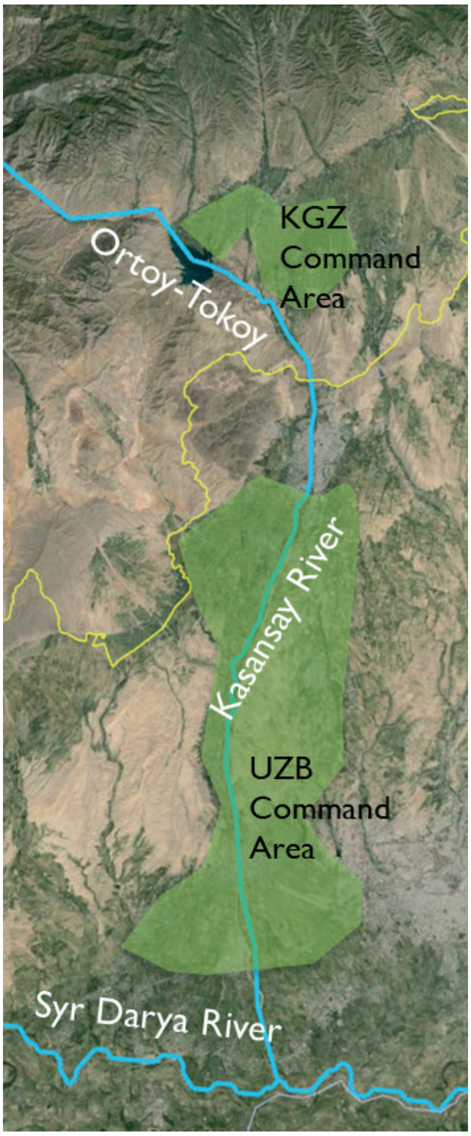


Figure 51. Location of Orto-Tokoy reservoir along Kasansay River

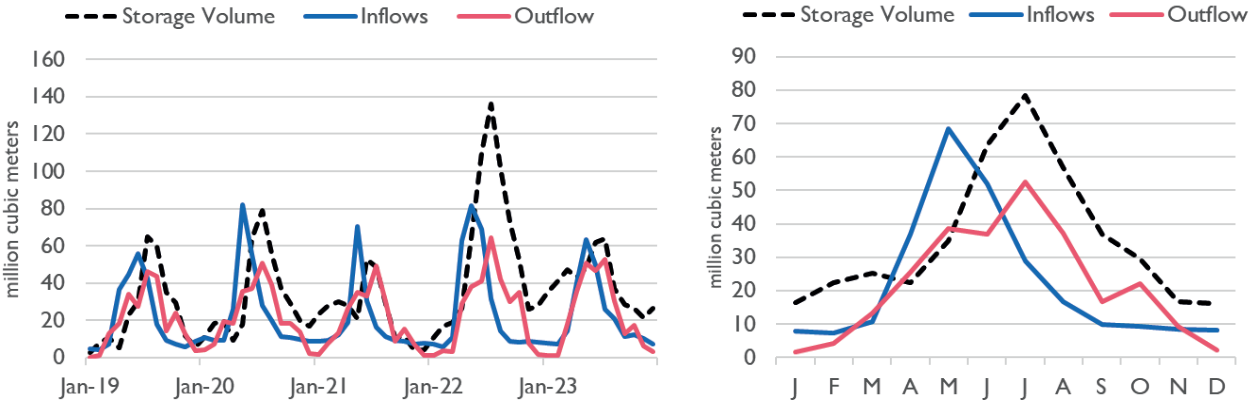


Figure 52. Observed inflows, outflows, and storage volume at Oro-Tokoy reservoir (2019-2023)

Objectives

The objectives of the Orto-Tokoy case study were to utilize the WEAP model for evaluating various water management scenarios under three climate projections: historical, dry, and wet. The study aimed to assess the impacts of these climate projections on water resources and to explore adaptive strategies for sustainable water management in the region.

Scenarios

In the WEAP model used for the Orto-Tokoy case study, three main management scenarios were considered:

1. **Baseline Scenario:** This scenario represents the current operational regime of the Orto-Tokoy dam and reservoir. It serves as a reference point against which other scenarios are compared. The baseline scenario reflects the existing conditions and management practices without any significant changes to infrastructure or operational procedures.
2. **Dredging Scenario:** This scenario focuses on maintaining usable storage within Orto-Tokoy reservoir by regularly removing sediments, such that dead storage remains fixed at 10 million cubic meters. Otherwise, this scenario assumes the same operational regime as the Baseline.
3. **Reservoir Expansion Scenario:** This scenario explores the potential impact of increasing the storage capacity of the Orto-Tokoy reservoir from 165 million cubic meters to 525 million cubic meters (Figure 53). By expanding the reservoir's capacity, the scenario aims to assess how enhanced storage capabilities could influence water management objectives, such as improved water availability, flood control, hydropower generation, and overall water resource sustainability.

These scenarios allow for the evaluation of different management strategies and infrastructure changes within the WEAP model framework, helping to inform decision-making regarding future water management practices at the Orto-Tokoy reservoir.

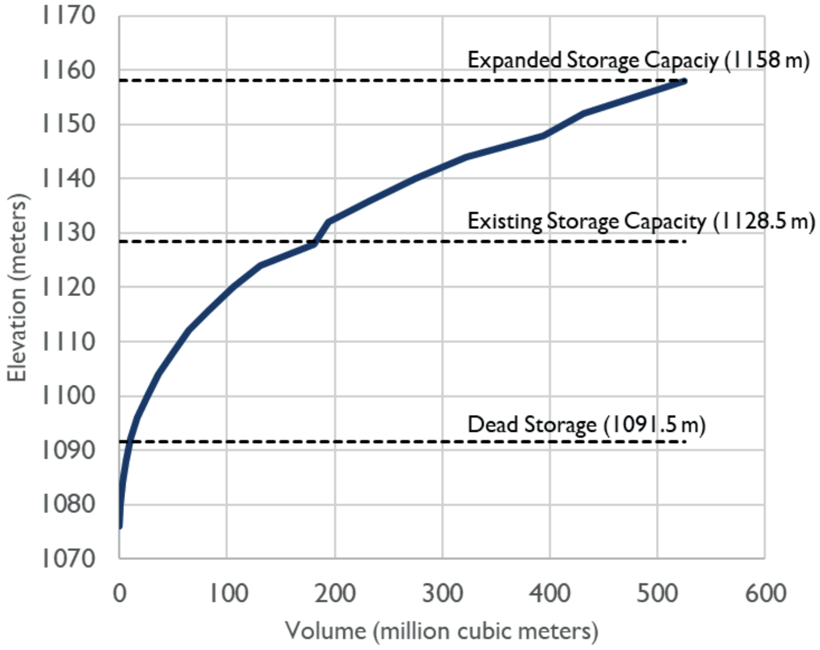


Figure 53. Orto-Tokoy reservoir storage profiles: Current vs. Expanded Capacity

Results

The case study results focus on two primary aspects: the impacts of climate variability on total water availability, encompassing reservoir inflows and storage volumes, and the effects of different management scenarios on balancing water storage and water delivery. By examining how historical, dry, and wet climate projections influence water resources, the study provides insights into the resilience of water availability in the Orto-Tokoy region under varying climatic conditions. Additionally, the evaluation of management scenarios, including baseline operations and an expanded reservoir capacity scenario, sheds light on potential strategies to optimize water delivery, manage risks associated with different climate variations, and enhance the overall sustainability of water resources in the study area.

Reservoir Inflows

Significant variations in reservoir inflow were observed across different climate projections (Table 9 and Figure 54). Under historical climatic projection, the average annual inflow into the Orto-Tokoy reservoir was estimated to be 444 million cubic meters. In contrast, the dry climate projection resulted in a 20% reduction in inflows, bringing the average annual inflow down to 356 million cubic meters. Conversely, the wet climate projection saw a 20% increase in inflows, with an average annual inflow rising to 534 million cubic meters. These results highlight the substantial influence of climate variability on reservoir inflows, underscoring the importance of adaptive water management strategies to mitigate risks associated with changing climatic conditions.

Table 9. Average annual reservoir inflows under historical, dry, and wet climate projections.

Climate Projection	Average Annual Inflow (mln m^3)	Percent Change from Historical (1985-2014)
Historical	444	
Dry	356	-20%
Wet	534	20%

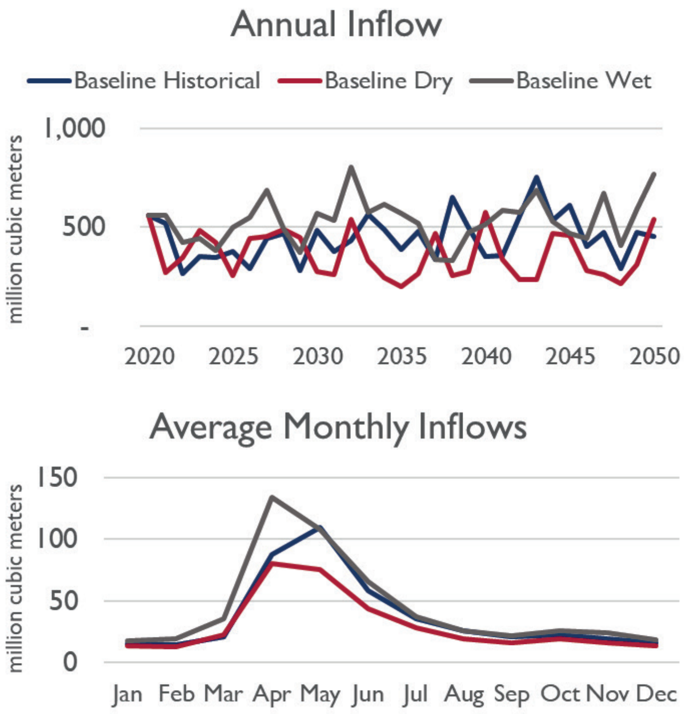


Figure 54. Reservoir inflows under historical, dry, and wet climate projections.

Reservoir Storage

The WEAP model results for reservoir storage volumes under the Baseline, Reservoir Expansion, and Dredging scenarios reveal distinct patterns influenced by climate projections. First, the Baseline and Dredging scenarios exhibit very similar storage patterns, with getting drawn down slightly more than the Baseline – i.e. to 10 million cubic meters versus an average of 15.8 million cubic meters under the Baseline. This implies that the Dredging scenario has access to an additional 5.8 million cubic meters of water each year.

In both the Baseline and Dredging scenarios, reservoir storage is regularly drawn down as part of normal operations. Under historical climate projection, inflows are sufficient to maintain standard operational levels. However, despite significantly higher inflows under the wet climate projection, there is no additional storage benefit, and the reservoir does not refill more frequently than it does under historical conditions. Conversely, under the dry climate projection, the reservoir struggles to refill, highlighting the challenges of maintaining adequate storage levels during periods of reduced water availability.

In the Reservoir Expansion scenario, storage volumes are generally much higher across all climate projections compared to the Baseline scenario. The increased storage capacity allows for better water retention and management. Under the wet climate projection, the expanded storage capacity results in higher storage levels than the historical climate projection, effectively capturing and utilizing the increased inflows. Although storage volumes under the dry climate projection continue to trend lower than both the historical and wet climate projections, the expanded capacity still provides some improvement in storage levels compared to the Baseline scenario. Overall, the Reservoir Storage scenario demonstrates enhanced resilience and capacity to manage varying climatic conditions, particularly under wet climate projection, whereas the Baseline scenario shows limitations in adapting to both dry and wet climate extremes.

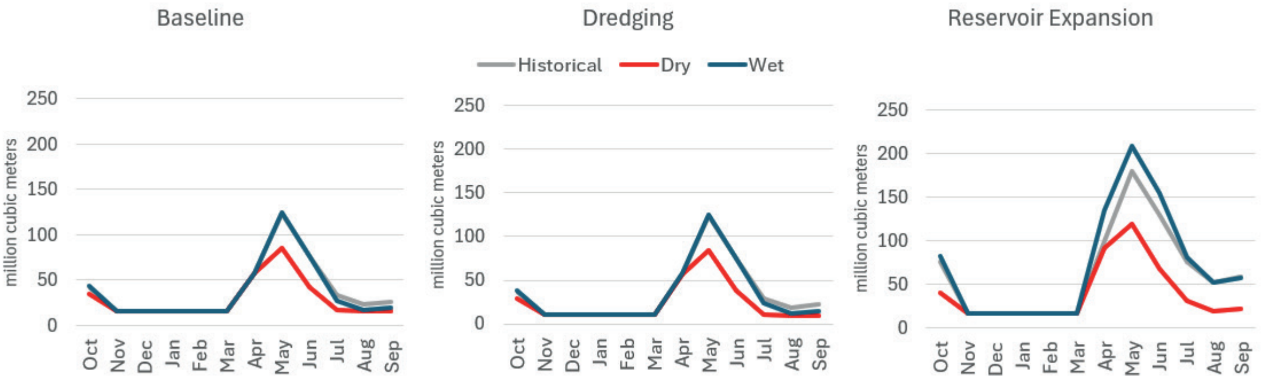


Figure 55. Reservoir storage volumes for Baseline, Dredging and Reservoir Expansion scenarios under historical, dry, and wet climate projections.

Water Deliveries

The WEAP model results for water deliveries from the Orto-Tokoy reservoir under the Baseline and Reservoir Expansion scenarios show distinct differences based on historical, dry, and wet climate projection. In the Baseline scenario under historical conditions, the average annual water delivery is estimated at 321 million cubic meters. When the dry climate projection is applied, water deliveries are reduced by 16 percent to 268 million cubic meters. Conversely, under the wet climate projection, water deliveries increase by 10 percent to 352 million cubic meters per year.

The Dredging scenario suggests a marginal increase in average annual water deliveries for each climate projection compared to the Baseline. Under each climate projection, average water deliveries increase by about 1 percent as compared to the same climate projection under the Baseline.

By contrast, the Reservoir Expansion scenario significantly enhances water delivery across all climate projections compared to the Baseline. Under the historical climate projection, total water deliveries increase by 7 percent relative to the Baseline. In the dry climate projection, water deliveries increase by 10 percent, demonstrating an improved ability to manage reduced inflows. Under the wet climate projection, the expansion leads to a 12 percent increase in water deliveries, maximizing the utilization of higher inflows. Overall, the Reservoir Expansion scenario significantly improves water delivery resilience and capacity across varying climatic conditions.

Table 10. Average annual water deliveries from Orto-Tokoy for Baseline and Reservoir Expansion scenarios under historical, dry, and wet climate projections

Scenario	Average Annual Deliveries	Percent Change from Baseline with Same Climate Projections (1985-2014)
Baseline – Historical	318	
Baseline – Dry	263	-17%
Baseline – Wet	347	+9%
Dredging – Historical	322	+1%
Dredging – Dry	268	-16%
Dredging - Wet	352	+11%
Reservoir Expansion – Historical	344	+8%
Reservoir Expansion – Dry	293	-8%
Reservoir Expansion – Wet	393	+24%

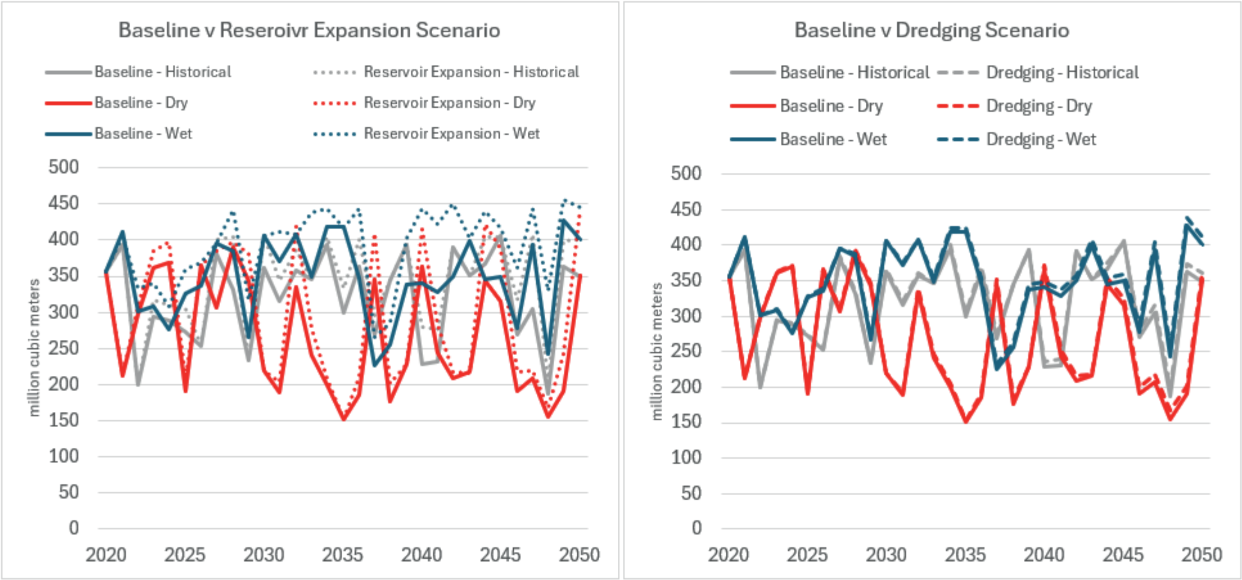


Figure 56. Water deliveries from Orto-Tokoy for Baseline, Dredging and Reservoir Expansion scenarios under historical, dry, and wet climate projections

Conclusions and Recommendations

The WEAP model analysis for the Orto-Tokoy reservoir under various climate projections and management scenarios provides valuable insights into the impacts of climate variability and the benefits of reservoir capacity expansion on water management. The results highlight significant differences in reservoir inflows, storage volumes, and water deliveries under historical, dry, and wet climate projections.

Conclusions:

1. **Climate Projections Impact on Inflows:** The reservoir inflows are highly sensitive to climatic projections, with inflows decreasing by 20 percent under dry climate projection and increasing by 20 percent under wet climate projection compared to historical levels.

2. **Baseline Storage Limitations:** The Baseline scenario shows limited capacity to adapt to both dry and wet climate projections. In the dry climate projection, the reservoir struggles to refill, while in the wet climate projection, the increased inflows do not translate into additional storage benefits, indicating operational constraints.

3. **Marginal Benefit of Dredging:** The Dredging scenario suggest that removing sediments from the reservoir to create additional usable storage will have very little impact on managing water storage and deliveries.

4. **Enhanced Storage Benefits:** The Reservoir Expansion scenario demonstrates significant improvements in storage volumes and water delivery capabilities. The expanded storage capacity allows for better retention and utilization of inflows, particularly under wet climate projection, and provides a buffer against reduced inflows during dry periods.

5. **Improved Water Deliveries:** Under the Reservoir Expansion scenario, water deliveries increase across all climate projections, with a 7 percent increase under historical conditions, a 10 percent increase under dry conditions, and a 12 percent increase under wet conditions. This highlights the enhanced resilience and operational flexibility provided by the expanded reservoir capacity.

Recommendations:

1. **Implement Reservoir Expansion:** Given the substantial benefits observed in the Reservoir Expansion scenario, it is recommended to increase the storage capacity of the Orto-Tokoy reservoir from 165 million cubic meters to 525 million cubic meters. This expansion would improve water availability, enhance flood control, and support sustainable water management under varying climate projections.

2. **Adaptive Management Strategies:** Develop and implement adaptive management strategies that account for water levels variability. This includes optimizing reservoir operations to maximize storage and water delivery benefits during wet periods and maintaining adequate reserves during dry periods.

3. **Monitor and Adjust Operations:** Continuously monitor water-level trends and reservoir performance to adjust operational strategies in real-time. This proactive approach will help mitigate the impacts of extreme weather events and ensure the reliability of water supplies.

4. **Stakeholder Engagement:** Engage with local stakeholders, including communities, agricultural users, and industry, to ensure that water management strategies align with their needs and priorities. Collaborative planning and decision-making will enhance the effectiveness and acceptance of proposed interventions.

5. **Further Research:** Conduct further research to refine climate projections and improve the accuracy of hydrological models. This will support more precise planning and management of water resources in the face of different variabilities.

Implementing these recommendations will enhance the resilience and sustainability of water resources in the Orto-Tokoy region, ensuring reliable water supplies for various uses.

CONCLUSIONS

This Activity clearly demonstrates the value of taking an integrated approach to water-energy-food modeling as opposed to modeling in silos. The highlights of the value include:

- **Linking LEAP and WEAP changes the results for hydropower**
- **Linking LEAP and Macro gives more complex GDP trajectories**
- **Linking WEAP and Macro captures how water availability affects the economy**
- **Linking LEAP, WEAP and Macro combines these feedbacks**

These changes are particularly significant in LEAP results. Not considering impacts of different climate projections on water resources and competing water demands on energy systems may results in misplaced investments of as much as 8.3 Billion 2020 USD dry climate projection. Financial risks associated with misplaced energy systems investment are greatest in Tajikistan due to its dependence on hydropower (5.39 Billion 2020 USD), and Uzbekistan due to the size of its energy system (2.31 Billion 2020 USD).

The changes are less significant in WEAP, particularly relative to what was observed in the Syr Darya river basin. This is related to the geography of the location of hydropower relative to irrigated agriculture. But given the impact on the LEAP results, there is clear value in the integration. Due to a lack of data, the degree to which Macro impacted results is less clear, given only one of the four countries had a Macro model.

From the integrated results, modeling results indicate that as the four riparian countries of the Amu Darya basin develop over the next three decades energy demand and electricity supply will grow 7-fold and require substantial new capacity developments. New hydropower capacity plays an important role in national plans, especially in Tajikistan, but impacts of different climate projections on water availability together with increases in water demands across the region indicate that the new hydropower capacity developments might experience substantial variability and shortfalls going forward. These will need to be compensated by additional fossil and renewable energy capacity in all four riparian countries. Improved agricultural practices and energy and climate mitigation policies have the potential to reduce the need for additional capacity, and hence costs. Improved cooperation around water between upstream and downstream countries provides an opportunity to improve agricultural outcomes, but increases required investments in the energy system, as well as GHG emissions.

The Activity demonstrates the potential value of using these tools for more local case studies with two applications, the Tuyamuyun Reservoir and the Orto-Tokoy (Kasansay) Reservoir. Each looked at a range of scenarios, including changes in storage, as well as the deep uncertainty around the potential annual diversions of 13 billion cubic meters to the Qosh Tepa Canal in Afghanistan under the Tuyamuyun Reservoir Case Study. Both show promise in terms of informing policy but would require deeper dive analyses to find more robust and realistic solutions with costing information as well.

The Activity was able to bring together actors across countries and sectors in a multi-year process using RDS and a Nexus approach. The approach demonstrated the value of not only modeling across sectors, but fostering discussions that in the end will lead to more robust and sustainable results with better economic outcomes. Collaboration and cooperation will create the environment for sustainable development throughout the region.

ANNEX A:

DETAILED SCENARIO IMPLEMENTATION

Scenario S1: Baseline

Kazakhstan

- Substantial growth in agricultural value added by 2050 (target: 5x 2013-2050) (President of the Republic of Kazakhstan 2012)
- 80.8% growth in real manufacturing value added 2018-2025 (Government of the Republic of Kazakhstan 2019)
- Decrease in electricity system reserve margin to 2030 (Government of the Republic of Kazakhstan 2014)

Kyrgyz Republic

- Real GDP growth rate 5% during 2023-2026, 2.5% during 2030-2050 (Government of the Kyrgyz Republic 2021a; Government of the Kyrgyz Republic 2021b)
- Per capita income reaches 1500 2021 USD in 2026 (Government of the Kyrgyz Republic 2021a)
- Reconstruction of At-Bashi, Uch-Kurgan, and Toktogul hydropower facilities (Government of the Kyrgyz Republic 2018)
- At least 30% growth in air traffic 2018-2023 (Government of the Kyrgyz Republic 2018)
- Expansion of Kambarata 2 (Government of the Kyrgyz Republic 2018)
- Construction of Kambarata 1, Upper Naryn HPP Cascade, Suusamyr-Kokomeren HPP Cascade, Kazarman HPP Cascade (Government of the Kyrgyz Republic 2018; Government of the Kyrgyz Republic 2021a)
- 300-400 MW of new small hydropower by 2026 (Government of the Kyrgyz Republic 2021a)

Tajikistan

- 6% annual growth in real GDP through 2030 (Republic of Tajikistan 2021)
- GDP shares by 2025: industry 25%, agriculture 19%, services 33% (Government of the Republic of Tajikistan 2021)
- 400-450 MW new coal combined heat & power by 2025 (Government of the Republic of Tajikistan 2021)
- Electricity transmission and distribution losses reduced to 12% by 2025 (Government of the Republic of Tajikistan 2021)
- Reconstruction of Kairokkum, Nurek, and Sarband (Golovnaya) hydroelectric plants (Government of the Republic of Tajikistan 2021)
- Construction of following hydropower plants: Rogun, Shurob, Sanobodskaya, Sebzor, Zeravshan river basin (Government of the Republic of Tajikistan 2021)
- Electricity exports reach 5 billion kWh by 2025 (Government of the Republic of Tajikistan 2021)

Turkmenistan

- 2% average annual growth in real GDP through 2050 (IMF 2021)

Uzbekistan

- Per capita income reaches $4k 2021 USD by 2030 (President of the Republic of Uzbekistan 2022)
- 1.4x growth in industrial value added 2021-2026 (President of the Republic of Uzbekistan 2022)
- Chemical and petrochemical value added attains $2B 2021 USD by 2026 (President of the Republic of Uzbekistan 2022)
- 2.8x growth in wood and wood products value added 2021-2026 (President of the Republic of Uzbekistan 2022)

- Doubling of textile and leather value added 2021-2026 (President of the Republic of Uzbekistan 2022)
- 1.4x growth in transport equipment value added 2021-2026 (President of the Republic of Uzbekistan 2022)
- Electricity generation grows 30 billion kWh 2021-2026 (President of the Republic of Uzbekistan 2022)
- Agricultural value added grows 5% annually during 2021-2026 (President of the Republic of Uzbekistan 2022)

Scenario S2: Agricultural efficiency

No changes in model-specific inputs compared to S1; hydropower availabilities and energy demand for water pumping are updated based on WEAP.

Scenario S3: Energy & Climate policies

Kazakhstan

- 10% decrease in electricity intensity of production of non-ferrous metals, ferrous metals, and chemicals 2021-2025 (Republic of Kazakhstan 2021)
- 15% decrease in energy consumption in residential sector 2021-2025 (Republic of Kazakhstan 2021)
- 50% of conventional road transport switched to electricity by 2050 (assumption developed with WAVE stakeholders)
- Heat production efficiency increases to 90% by 2030 (President of the Republic of Kazakhstan 2013)
- Heat transmission and distribution losses reduced to 10% by 2030 (President of the Republic of Kazakhstan 2013)
- Solar, wind, hydro, nuclear, and gas electricity generation: 55% of national total by 2030, 100% by 2050 (President of the Republic of Kazakhstan 2013)
- 12 MTOE of energy efficiency savings realized by 2030 (Government of the Republic of Kazakhstan 2014)
- Reduction of energy intensity of GDP (2008 baseline) – 30% by 2030, 50% by 2050 (President of the Republic of Kazakhstan 2013)
- Reduction of CO2 emissions from power generation (2012 baseline) – 15% by 2030, 40% by 2050 (President of the Republic of Kazakhstan 2013)
- 15% reduction in economy-wide GHG emissions by 2030 (1990 baseline) (Republic of Kazakhstan 2016)

Kyrgyz Republic

- 60% electrification of rail transport by 2040 (Government of the Kyrgyz Republic 2018)
- 11.6% reduction in electricity transmission and distribution losses 2018-2023 (Government of the Kyrgyz Republic 2018)
- 10% renewables in total primary energy supply by 2040 (Government of the Kyrgyz Republic 2018)
- Other climate change mitigation measures from NDC (Government of the Kyrgyz Republic 2021b)
    - Reducing coal consumption through gasification of households
    - Improving Traffic Management and Cycling Infrastructure Development

    - Replacement of buses with diesel/gasoline fuel engines by buses with gas-powered engines in Bishkek
    - Construction of new buildings according to energy efficient CSR

Tajikistan

- Energy sector GHG emissions decrease to between 12.8 and 15.0 $MtCO_2e$ by 2030 (Republic of Tajikistan 2021)
- 10% decrease in commercial and residential electricity intensity by 2024 (Gauss International Consulting S.L. 2020)
- Commercial and residential coal demand switched to electricity by 2030 (Gauss International Consulting S.L. 2020)
- 10% improvement in industrial energy efficiency by 2030 (SEI assumption informed by NDC)
- 65% of gasoline and diesel road transport switched to gas by 2026 (Gauss International Consulting S.L. 2020)
- 50% of conventional road transport switched to electricity by 2050 (SEI assumption informed by NDC)
- 15% decrease in energy intensities of international bunkers, non-energy uses of energy, and other miscellaneous energy uses by 2030 (SEI assumption informed by NDC)
- 83% renewable electricity by 2030 (SEI assumption informed by NDC)

Turkmenistan

- Reduction in electricity demand for street lighting from installation of 162,000 new LEDs by 2024[6] (SEI assumption informed by NDC measure)
- Reduction in transmission losses due to upgrading 738 transformers by 2030[7] (SEI assumption informed by NDC)

Uzbekistan

- 50% of conventional road transport switched to electricity by 2050 (President of the Republic of Uzbekistan 2022)
- 60% of rail transport electrified by 2026 (President of the Republic of Uzbekistan 2022)
- 20% improvement in industrial energy efficiency 2019-2030 (President of the Republic of Uzbekistan 2019)
- 25% of electricity generation from renewables by 2026 (President of the Republic of Uzbekistan 2022)
- 5 GW new solar, 3 GW new wind, and 1.9 GW of new hydro electricity generating capacity 2022-2030 (Republic of Uzbekistan 2021)
- 50% decrease in energy intensity of GDP 2010-2030 (Republic of Uzbekistan 2021)
- 35% reduction in GHG intensity of GDP 2010-2030 (Republic of Uzbekistan 2021)

Scenarios S4: Cooperation

No changes in model-specific inputs compared to S3; hydropower availabilities and energy demand for water pumping are updated based on WEAP.

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[6] Government of Turkmenistan (2022). Nationally Determined Contribution under the Paris Agreement. https://unfccc.int/sites/default/files/NDC/2023-01/NDC_Turkmenistan_12-05-2022_approv.%20by%20Decree_Rus.pdf

[7] Overnment of Turkmenistan (2022). Nationally Determined Contribution under the Paris Agreement. https://unfccc.int/sites/default/files/NDC/2023-01/NDC_Turkmenistan_12-05-2022_approv.%20by%20Decree_Rus.pdf.

ANNEX B:

LEAP MODEL DETAILS

General overview

The energy systems model used in the RDS analysis was built with three pieces of software: LEAP, the Next Energy Modeling system for Optimization (NEMO), and the Gurobi Optimizer solver. LEAP is the main component in this platform and provides user and application programming interfaces to the model. These support changing the model's inputs and formulas, calculating the model, and reviewing and visualizing results.

LEAP is a software tool for quantitative modeling of energy systems, greenhouse gas (GHG) and air pollutant emissions, costs and benefits, health impacts, and other environmental externalities. Produced by SEI, it is among the most widely used energy system modeling and climate change mitigation planning tools in the world.

NEMO[8] is a high-performance, open-source energy system optimization tool. Although it can be run in stand-alone mode, it is designed to integrate with LEAP as a user interface. NEMO simulates energy systems through least-cost optimization – finding the most cost-effective way to meet energy requirements in all modeled years. The energy systems model for the RDS analysis uses NEMO to simulate electricity production. Like LEAP, NEMO is developed by SEI.

When NEMO is run, it formulates an optimization problem based on the model it is calculating. It then uses a separate solver program to solve the problem. NEMO is compatible with many different solvers, including open-source and commercial/proprietary options. The modeling results presented in this report were calculated with the commercial Gurobi Optimizer solver. SEI used this solver because of its superior performance with complex models.

Although the energy systems model used in the RDS analysis is built on LEAP, NEMO, and Gurobi Optimizer, this report refers to it as the "LEAP model" for simplicity's sake.

LEAP scope and structure for Amu Darya

Model coverage and internal structure

The LEAP model simulates the energy systems of Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan from 2010 to 2050. It represents all sources of energy demand and supply in these countries, including all fuels or energy carriers[9]. The energy simulation extends from final energy demands through the transportation and distribution of fuels, fuel production, primary energy extraction, and energy trade. The model calculates GHG emissions from energy production and consumption (carbon dioxide, methane, and nitrous oxide) as well as the direct costs of energy demand and supply in some cases (electricity production, water pumping).

Each of the five Central Asian countries is represented as a separate region in the model. Most of the modeling of energy demand, energy supply, emissions, and costs is geographically aggregated to the regional level. For example, demands for heat are calculated for each region (country) rather than for provinces, cities, or other subnational areas within each country. The model was designed to integrate with the WEAP model for the Amu Darya and Syr Darya Basins, however, there are exceptions to this approach for three components of the energy systems with important implications for water: hydropower production, agricultural energy demand, and energy demand for water pumping. In these cases, the modeling within each country is further disaggregated by basin.

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[8] Its source code and documentation are available through https://www.sei.org/tools/nemo-the-next-energy-modeling-system-for-optimization/, and an installer for NEMO is distributed via the LEAP website. Because NEMO is open source, it is freely available to all users.

[9] The terms «fuel» and «energy carrier» are used interchangeably in this report.

The LEAP model includes a historical period, for which it reproduces historical energy demand and supply, and projection years, for which it simulates the evolution of the national energy systems. In most cases (but depending on the specific variable), the historical period is 2010-2019, and projections run from 2020 to 2050. The model comprises multiple projections corresponding to different scenarios, including a baseline scenario and scenarios exploring particular policies (these are discussed in detail in section 4). The default time step in the model is annual, meaning that inputs and outputs are defined with annual resolution. However, for increased realism, the modeling of electricity demand and supply is performed with sub-annual time steps: 288 time slices per year, representing a typical 24-hour day in each month.

LEAP supports disaggregating models by various user-defined categories in addition to geographic regions and time steps. The LEAP model for the RDS analysis takes advantage of this capability to further structure its simulation of energy supply and demand. Final energy demands are classified by sector/subsector and fuel, including the following sectoral designations:

- Agriculture
- Commercial
- Industry
    - Chemical and petrochemical
    - Construction
    - Food and tobacco
    - Iron and steel
    - Machinery
    - Mining and quarrying
    - Non ferrous metals
    - Non metallic minerals
    - Other
    - Paper, pulp, and printing
    - Textiles and leather
    - Transport equipment
    - Wood and wood products
- Residential
    - Urban
    - Rural
- Transport
    - Domestic aviation
    - Domestic navigation
    - Other
    - Pipelines
    - Rail
    - Road

The energy demand modeling also covers international bunkers, non-energy uses of fuels (e.g., as feedstocks in chemical manufacturing), statistical differences, and other energy demands that cannot be attributed to any of the foregoing sectors.

On the supply side of the model, energy production is broken down by sector or industry, technology, and fuel. Modeled sectors or industries include:

- Biomass production
- Blast furnaces
- Brown coal briquettes production
- Charcoal production
- Coal mines (for various types of coal – anthracitic, bituminous, and lignite)

- Coke ovens
- Electricity production
- Fossil gas production
- Gas to liquids production
- Hard coal briquettes production
- Heat production
- Oil production
- Oil refineries

For each sector/industry, the model represents energy use, energy production, and emissions. It also accounts for transfers of energy between sectors, changes in energy stocks or inventories, and losses in energy transportation, transmission, and distribution.

The modeling of electricity supply separately represents major existing, planned, and potential hydropower facilities in the Amu Darya and Syr Darya Basins – 53 in all. These are connected to the WEAP modeling when the LEAP and WEAP models are run in integrated mode. Other electricity supply facilities are aggregated by technology (33 in total), including various coal, fossil gas, oil, nuclear, and renewable technologies. Table 11 lists the electricity production technologies and hydropower facilities in the LEAP model and indicates the countries in which they are activated. As the table shows, only certain technologies are activated in each country. Active technologies include those that are currently used in a country, that are foreseen in national plans or policies, and (in the case of wind and solar) that are possible to build given available renewable resources.

Table 11. Electricity production technologies and hydropower plants in each country of the LEAP model

Plant or technology	KAZ	KGZ	TJK	TKM	UZB
Biogas internal combustion CHP	X				
Coal bituminous fossil gas subcritical steam CHP		X			
Coal bituminous oil subcritical steam	X				
Coal bituminous oil subcritical steam CHP	X				
Coal bituminous subcritical steam					
Coal bituminous subcritical steam CHP	X	X	X		
Coal bituminous supercritical steam	X				
Coal bituminous supercritical steam CHP	X				
Coal lignite subcritical steam					X
Coal lignite supercritical steam CHP					X
Diesel internal combustion		X			
Dual fuel combined cycle	X				
Dual fuel open cycle				X	
Dual fuel subcritical steam	X			X	X
Dual fuel subcritical steam CHP	X	X	X	X	X
Dual fuel supercritical steam					X
Fossil gas combined cycle				X	X
Fossil gas combined cycle CHP	X				X
Fossil gas internal combustion CHP	X				
Fossil gas open cycle	X			X	
Fossil gas open cycle CHP	X			X	X
Fossil gas subcritical steam	X				X

Plant or technology	KAZ	KGZ	TJK	TKM	UZB
Fossil gas subcritical steam CHP	X		X	X	X
Fossil gas supercritical steam					X
Hydropower large	X	X	X		X
Hydropower small	X	X	X	X	X
Nuclear	X				X
Oil steam					X
Oil steam CHP	X			X	
Solar photovoltaic	X	X	X	X	X
Wind onshore excellent CF	X	X	X		
Wind onshore good CF	X	X	X	X	X
Wind onshore very good CF	X	X	X	X	X
AKHANGARAN RESERVOIR					X
AKKAVAK_1					X
ANDIJAN_1					X
ANDIJAN_2					X
AT_BASHIN		X			
AYNI			X		
BACHISHAMAL 2					X
BAIPAZA			X		
CHARVAK					X
CHIRCHIK_1					X
CHIRCHIK_2					X
DARAUT KURGAN		X			
DASHTIJUM			X		
FARKHAD					X
GAZALKENT					X
GISSARAK					X
GOLOVNAYA			X		
HAZARBAHSKAYA					X
KAIRAKKUM			X		
KAMBARATA_1		X			
KAMBARATA_2		X			
KAPHTARGUZAR			X		
KAZARMAN CASCADE		X			
KHISHRAUS					X
KHODZHIKENT					X
KUMKURGAN					X
KURPSAI		X			
NILYU 2					X
NUREK			X		
NUROBOD			X		

Plant or technology	KAZ	KGZ	TJK	TKM	UZB
PAMIR 1			X		
PAMIR 2			X		
PEREPADNAYA KHATLON			X		
ROGUN			X		
SANGTUDA 1			X		
SANGTUDA 2			X		
SARVOZ			X		
SHAMALDYSAI		X			
SHARDARINSKYA	X				
SICHANKUL CANAL					X
SUUSAMYR_KOKOMEREN CASCADE		X			
TASH_KUMYR		X			
TAVAK					X
TOKTOGUL		X			
TSENTRALNAYA TAJIK			X		
TUPOLANG 1					X
TYUYAMUYUNSKAYA					X
UCH_KURGANSK		X			
UPPER NARYN CASCADE		X			
VARZOB 2			X		
ZARCHOB 1					X
ZARCHOB 2					X
ZARCHOB 3					X

As part of its simulation of primary energy extraction, the LEAP model tracks endowments of primary energy in each country. These comprise reserves of non-renewable energy (coal, fossil gas, and oil) and annual potential or yields of renewable energy (biomass, hydro, solar, and wind).

Modeling methods, input data, and assumptions

The energy, cost, and emissions calculations in the LEAP model occur within an accounting framework provided by the LEAP software. This framework is common to all LEAP models that cover energy systems and energy-related emissions and costs. Emissions are calculated by multiplying energy production and consumption by emission factors, which are specific to pollutants, fuels, sectors, activities, and technologies in the model. Costs are calculated on the basis of unit costs of technologies and activities that produce or consume energy. The unit costs, which include capital, operations, and maintenance costs in the model, are multiplied by levels of technology deployment, technology use, or activity. In this way, both emissions and costs depend on the energy modeling.

For the energy simulation, LEAP's accounting framework establishes an order of calculations and ensures internal coherence. The simulation takes place in each region and time step and starts with final energy demands. Once final demands by fuel are computed, LEAP uses the model's energy supply sectors to respond to the demands. Sectors are mobilized as needed to meet demands, subject to production capacity and primary resource constraints. As the supply system operates, it may create intermediate energy demands (e.g., coal for electricity generation, losses in electrical lines), which must also be satisfied in each region and time step.

The model fulfills as much of the demand for each fuel as possible with local (in-region) supply. If demands remain after local energy supply sectors have been fully utilized, LEAP can meet them with imports or report them as unmet. If a supply sector creates a surplus of a fuel, LEAP can treat it as exported or wasted. The LEAP model for the RDS analysis assumes any residual demands are covered with imports, and any surpluses are exported. Due to data limitations, the model does not keep track of the origins of imports or the destinations of exports, although this is possible in LEAP.

Within this overall accounting framework, LEAP supports various methods for simulating how much final energy is demanded and which supply options produce the required fuels. The model for the RDS analysis combines different methods on its demand and supply sides. The principal method for determining final energy demand is activity analysis, which calculates demand as the product of an activity level and an energy intensity. In historical years, these are based on historical data (so the model reproduces historical energy consumption); in subsequent years, activity levels and energy intensities are projected. Table 12 identifies the activity levels used in each final demand sector or category and factors that influence the projected energy intensities in the model's baseline scenario (S1).

Table 12 Key parameters for the modeling of final energy demand – activity levels and factors influencing baseline energy intensity.

Sector / category	Activity level	Drivers of changes in energy intensity
Agriculture – water pumping in Amu Darya and Syr Darya Basins	Volume of water pumped (from WEAP model)	None – intensities held constant
Agriculture – other	Agricultural value added	None – intensities held constant
Commercial	Commercial value added	Personal income, heating degree days, fuel prices
Industry – water pumping for industrial and domestic purposes in Amu Darya and Syr Darya Basins	Volume of water pumped (from WEAP model)	None – intensities held constant
Industry – all other demands	Industrial value added (subsectoral)	Fuel prices
Residential	Households	Personal income, heating and cooling degree days, fuel prices
Transport – road	Vehicle-kilometers	None – intensities held constant
Transport – rail, aviation, and navigation	Tonne-kilometers	Fuel prices
Transport – other	Gross domestic product (GDP)	None – intensities held constant
International bunkers, non-energy, other final demands	GDP	None – intensities held constant

To determine the drivers of changes in energy intensity, SEI conducted a statistical analysis of the relationship between historical intensities, personal income, heating and cooling degree days, and fuel prices (in each region). Relationships that were found to be statistically significant were included in the model.

As noted in Table 2, the model is designed to take projections of certain activity levels – volumes of water pumped – from the Activity water resources model. It is also designed to take projections of GDP and value added from the WAVE macroeconomic models (in the case of Kazakhstan and Kyrgyz Republic). In regions not covered by the macroeconomic models (Tajikistan, Turkmenistan and Uzbekistan), GDP and value added are projected based on trends and targets in national policies. The projection of households depends on historic household sizes and projected population from UN Department of Economic and Social Affairs (2019). Vehicle and tonne-kilometers are generally projected using their statistical relationship with GDP, unless national policies state a different future target or there is no statistically significant relationship with GDP (in which case the last observed historical value is held constant).

Future values of the drivers of changes in energy intensity are projected using complementary techniques. Personal income is calculated from projected population and GDP, while future fuel prices are based on prices and growth rates in International Energy Agency (2021d) and National Renewable Energy Laboratory (2021). Heating and cooling degree days are taken from climate model runs performed for the 6th Climate Model Intercomparison Project (CMIP6).

With respect to energy supply, the model is configured to reproduce historical records, notably International Energy Agency (2021c). Future energy supply is then projected with several simulation methods. Future electricity production is calculated via least cost optimization in NEMO. Subject to technical limits and accounting for cost and performance characteristics of power production options, the model finds the least costly way to supply electricity in every year and time slice. The optimization is conducted with perfect foresight and discounts all costs to the first simulation year (2020) at a 5% real discount rate. It covers both capacity expansion and dispatch – choosing what new production capacity to build and how to utilize the capacity that exists at each time step. There are some limits on the technologies the model can choose to build. Wind and solar capacity is limited by the potential of these resources; hydropower and biogas additions are restricted to replacing retiring facilities and building planned new hydropower facilities; and fossil and nuclear capacity is unlimited.

SEI calibrated the electricity optimization routine to historical energy balance data for 2010-2019. Calibration factors introduced in the model ensure that its short-term results align with the historical record in the Amu Darya countries' power systems. This design accounts for the fact that these systems may not be cost-optimizing today. Over time, the calibration factors are removed, simulating a progression toward more open and competitive power markets.

For future supply from other energy-producing sectors, the model performs a simple simulation in which the technologies and input fuels that have historically satisfied energy demands are assumed to continue doing so. Production capacity is not modeled, but the production of non-renewable primary energy (coal, oil, and gas) is limited by each country's reserves.

Losses in the transmission, distribution, and transport of energy are calculated using fuel-specific loss factors. For the most part, these are based on historical data, though in some countries future rates are modified by policy targets (e.g., a policy to reduce electricity transmission and distribution losses). As indicated earlier, electricity transmission and distribution capacity is not modeled due to a lack of necessary input data.

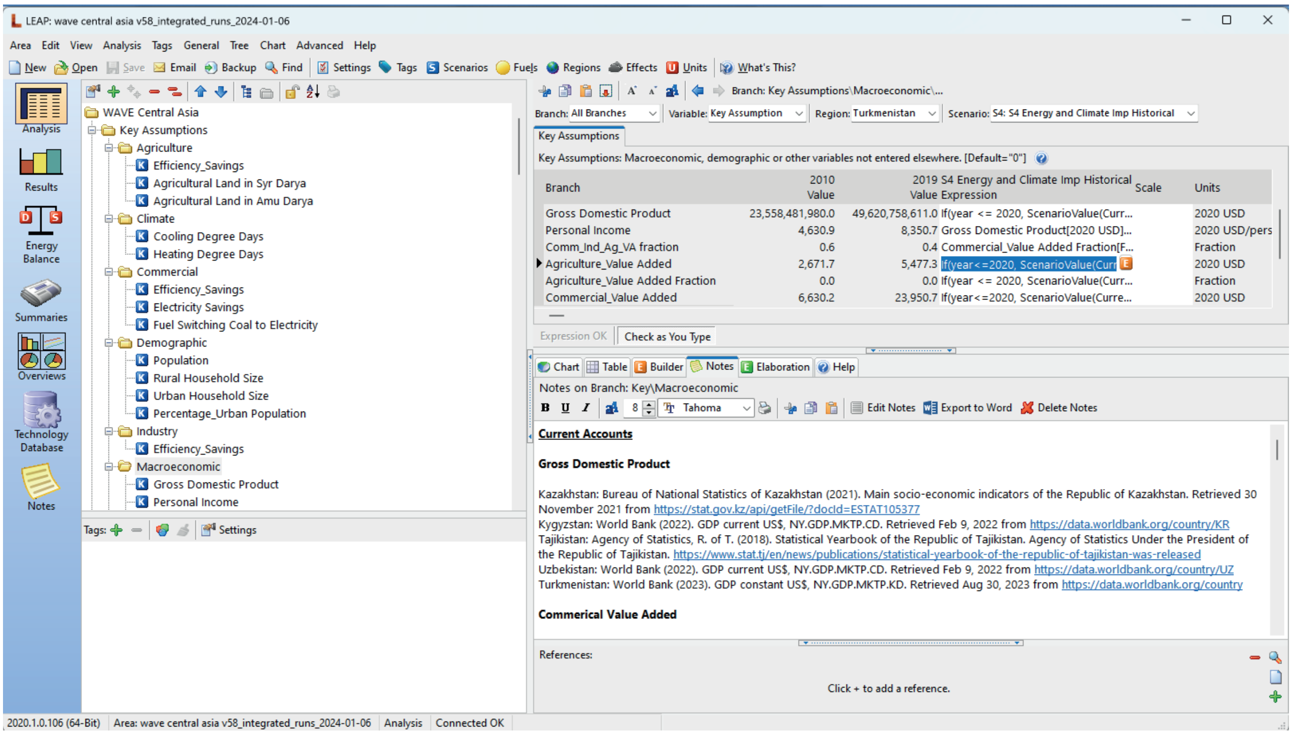
The discussion in the first part of this section described how the model allows imports to cover for energy supply shortages, and exports to absorb energy surpluses. In addition to this mechanism, the model assumes that historically observed energy imports and exports continue in the future. These imports and exports occur regardless of shortages or surpluses in the supply system.

Key input data used in the model include the following:

- Historical energy balances: International Energy Agency (2021c)
- Population: Bureau of National Statistics of Kazakhstan (2021b); Agency of Statistics, Republic of Tajikistan (2018); UN Department of Economic and Social Affairs(2019)
- GDP: Bureau of National Statistics of Kazakhstan (2021b); World Bank (2022); Agency of Statistics, Republic of Tajikistan (2018); World Bank (2022)
- Value added: Agency for Strategic planning and reforms of the Republic of Kazakhstan Bureau of National statistics (2022b; 2022a), National Statistical Committee of the Kyrgyz Republic (n.d.; 2021), Agency on Statistics under President of the Republic of Tajikistan (2022; n.d.), Bureau of National Statistics of Kazakhstan (2019; 2021a), Republic of Uzbekistan State Statistical Committee (2022a; 2022b; 2022c); World Bank (2023)
- Electricity production capacity: Platts (2021)

- Historical fuel prices: International Monetary Fund (2015; 2021)
- Reserves of non-renewable primary energy: BP (2021), International Energy Agency (2021b; 2021a; 2022)
- Solar and wind potentials: Eshchanov et al. (2019), Eshchanov et al. (2019)
- Import and export targets: International Energy Agency (2021c)

Further information on the model's inputs and methods is available in the model itself, found here: https://www.dropbox.com/scl/fi/0i5ihbj8n08k882xtxoqv/wave-central-asia-v58_integrated_runs_2024-01-04.leap?rlkey=gfoqfvvviuyxas3gf4ecla97p&dl=0. Input data are documented in the model using LEAP's Notes feature[10], which allows explanatory text and citations to be included in the model file (Figure 57).



Key Assumptions: Macroeconomic, demographic or other variables not entered elsewhere. [Default="0"]

Branch	2010 Value	2019 Value	S4 Energy and Climate Imp Historical Expression	Scale	Units
Gross Domestic Product	23,558,481,980.0	49,620,758,611.0	If(year <= 2020, ScenarioValue(Curr...		2020 USD
Personal Income	4,630.9	8,350.7	Gross Domestic Product[2020 USD]...		2020 USD/pers
Comm_Ind_Ag_VA fraction	0.6	0.4	Commercial_Value Added Fraction[F...		Fraction
Agriculture_Value Added	2,671.7	5,477.3	If(year<=2020, ScenarioValue(Curr		2020 USD
Agriculture_Value Added Fraction	0.0	0.0	If(year <= 2020, ScenarioValue(Curr...		Fraction
Commercial_Value Added	6,630.2	23,950.7	If(year<=2020, ScenarioValue(Curre...		2020 USD

Notes on Branch: Key\Macroeconomic

Current Accounts

Gross Domestic Product

Kazakhstan: Bureau of National Statistics of Kazakhstan (2021). Main socio-economic indicators of the Republic of Kazakhstan. Retrieved 30 November 2021 from https://stat.gov.kz/api/getFile/?docId=ESTAT105377
Kygyzstan: World Bank (2022). GDP current US$, NY.GDP.MKTP.CD. Retrieved Feb 9, 2022 from https://data.worldbank.org/country/KR
Tajikistan: Agency of Statistics, R. of T. (2018). Statistical Yearbook of the Republic of Tajikistan. Agency of Statistics Under the President of the Republic of Tajikistan. https://www.stat.tj/en/news/publications/statistical-yearbook-of-the-republic-of-tajikistan-was-released
Uzbekistan: World Bank (2022). GDP current US$, NY.GDP.MKTP.CD. Retrieved Feb 9, 2022 from https://data.worldbank.org/country/UZ
Turkmenistan: World Bank (2023). GDP constant US$, NY.GDP.MKTP.KD. Retrieved Aug 30, 2023 from https://data.worldbank.org/country

Commerical Value Added

References:

Click + to add a reference.

Figure 57. View of LEAP inputs including Notes feature

Model outputs

The model can generate a wide variety of outputs related to the Amu Darya countries' energy systems. These include energy demands by sector and fuel, total primary energy supply, domestic production of different energy carriers, energy imports and exports, non-renewable energy resource depletion, unmet energy requirements, and greenhouse gas emissions from energy production and consumption. In the power sector, generation, hourly dispatch, capacity additions and retirements, peak load, capacity factors, reserve margins, curtailment of renewables, and production costs can be reported. All of these results can be segmented by region, year, and other dimensions.

A key output for the Amu Darya analysis is dispatch of hydropower plants in the Amu Darya Basin. When the model is run in an integrated fashion with the WAVE water resources model, the water model determines the availability of water for hydropower, and the LEAP/NEMO model calculates how much water is actually used for hydropower. The two models iterate to seek convergent solution.

In addition to the above-mentioned results, LEAP and NEMO can provide various other outputs as described in their respective documentation (see Modeling platform). Users can also add custom output variables to the model using LEAP's Indicators feature.[11]

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[10] https://leap.sei.org/help/leap.htm#t=Screen_Layout%2FNotes.htm.

[11] https://leap.sei.org/help/leap.htm#t=Indicators%252FIndicators.htm.

ANNEX C:

WEAP MODEL DETAILS

WEAP is an integrated tool that seamlessly combines natural, climate-driven processes with the managed features of a water basin. This integration allows for a comprehensive analysis of both the supply and demand sides of water management.

WATER EVALUATION AND PLANNING (WEAP)

WEAP is an integrated tool that seamlessly combines natural, climate-driven processes with the managed features of a water basin. This integration allows for a comprehensive analysis of both the supply and demand sides of water management.

Within WEAP, climate-driven processes such as the accumulation and melting of snow and glaciers, rainfall runoff, and irrigation water requirements are dynamically incorporated to simulate the complex interactions between climate dynamics and water resources. By tracking snow and glacier accumulation and melting, WEAP captures the significant impact that these processes have on the timing of available water. The model's rainfall runoff capabilities allow for the assessment of surface water availability under varying precipitation patterns. Furthermore, WEAP accounts for irrigation water requirements, considering the spatial and temporal distribution of water demands for agricultural purposes.

In addition to climate-driven processes, WEAP incorporates various water management features such as reservoirs, hydropower plants, diversion canals, and irrigation infrastructure. These features allow for the representation of human interventions in water systems, facilitating the analysis of water allocation, reservoir operations, hydropower generation, and irrigation management strategies.

By integrating these diverse elements, WEAP provides a holistic view of water resource systems, enabling users to explore the implications of various scenarios and management strategies. This capability is crucial for planning and decision-making in the face of growing water demand, climate variability, and the need for sustainable water management practices.

WEAP Scope and Structure for Amu Darya

Through this comprehensive approach, the WEAP model aids in identifying strategies that balance water use for all sectors important for the economy, including such significant sectors as agriculture and energy production while minimizing negative environmental impacts. It provides a platform for stakeholders to explore trade-offs and synergies between different water uses, ultimately supporting more informed and sustainable water management decisions in the Amu Darya river basin.

Spatial Disaggregation of Water Supplies and Demands

To further enhance the model's precision, each sub-catchment was subdivided into 250-meter elevation bands. This finer level of disaggregation is crucial for capturing the accumulation and melting of snow and glaciers (Figure 58), as these processes are highly dependent on elevation and climate conditions. Each elevation band has unique climate sequences that influence snow and glacier dynamics as well as rainfall runoff, allowing the model to simulate these processes with greater accuracy.

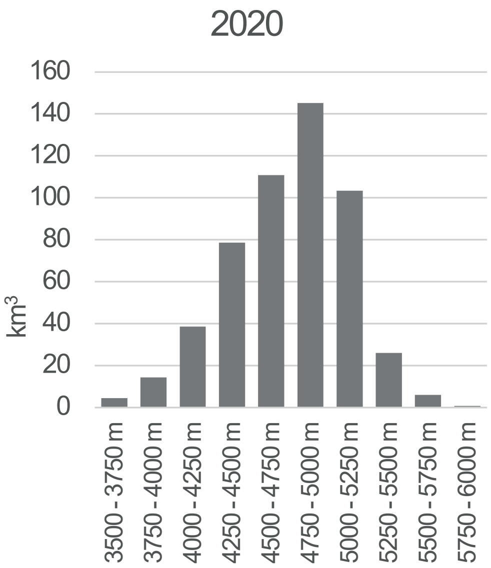

Figure 58. Distribution of glaciers for year 2020 at different elevations within the Amu Darya river basin

On the demand side, the spatial distribution of water demands was captured by defining water demand areas based on shared water sources (Figure 59). This approach helps in mapping out the specific regions that rely on the same water supplies for various uses, such as agriculture, domestic consumption, and industrial activities. By integrating these spatially disaggregated layers, the WEAP model provides a detailed and nuanced representation of both the supply and demand aspects of water management in the Amu Darya basin.

Figure 59. Grouping of demand areas within WEAP

Through this sophisticated spatial disaggregation, the WEAP model can simulate the complex interactions between climate-driven processes, infrastructural elements, and water use patterns. This allows for a more comprehensive evaluation of different water management strategies, aiding stakeholders in making informed decisions to balance the competing objectives of water, food, and energy in the basin.

Water Use Sectors

In the Amu Darya basin, the WEAP model considers several key water use sectors, each with distinct demands and impacts on the overall water resources. Domestic water use encompasses the water needs for household activities such as drinking, cooking, cleaning, and sanitation, which are essential for maintaining public health and quality of life for the basin's population. Industrial water use involves substantial water inputs for manufacturing and processing activities, varying based on the type and scale of operations, and is critical for economic development and job creation. Although it is non-consumptive, hydropower generation is a significant use of water, providing a renewable energy source. The operation of hydropower plants involves the controlled release of water from reservoirs, impacting downstream water availability and timing.

Agriculture represents the largest consumptive water use sector in the basin, with extensive irrigation systems supporting crop cultivation. Irrigation is crucial for food security and the livelihoods of local communities but also draws heavily on water resources. Additionally, ecological flows refer to the water required to maintain healthy ecosystems within the basin, including wetlands, rivers, and other aquatic habitats that support biodiversity and provide ecosystem services. Ensuring adequate ecological flows is vital for preserving environmental health and resilience. By considering these diverse water use sectors, the WEAP model provides a comprehensive framework for evaluating and managing the competing demands on the Amu Darya basin's water resources.

Allocation to Water Use Sectors

WEAP uses a system of priorities to determine allocations from supplies to demand sites and catchments, for instream flow requirements, filling reservoirs, and generating hydropower. For the Amu Darya model, we used a two-tier priority structure in which the first tier was determined by water users' position within the watershed and the second tier was based on water use sectors. In this configuration, water users in the upper part of the basin were given the highest priority, assuming that they would choose to use available supplies before releasing water downstream. Within a demand region domestic demands are assigned the highest priority. In Tajikistan, hydropower is assigned the second highest priority, followed by agriculture, industry, water storage, and ecosystem. In contrast, in Turkmenistan and Uzbekistan, irrigation and industry are assigned the second highest priority, followed by hydropower, storage, and ecosystems. The demand priority structure is described in Table 13.

Table 13. Demand priority structure in WEAP

	Domestic	Hydropower	Irrigation	Industry	Ecosystems	Storage
TJK Dushanbe	1	2	3	3	99	4
TJK Vakhsh	1	2	3	3	99	4
TJK Kulyab	1	2	3	3	99	4
TKM Lebap	11	13	12	12	99	14
TKM Mary (Karakum Desert)	21	23	22	22	99	24
TKM Dashgovuz	21	23	22	22	99	24
UZB Surkhandarya (upstream & downstream)	1	3	2	2	99	4
UZB Kashkadarya (upstream & downstream)	1	3	2	2	99	4
UZB Zeravshan (upstream & downstream)	1	3	2	2	99	4
UZB Khorezm-Karakalpakstan	21	23	22	22	99	24

ANNEX D:

MACRO MODEL DETAILS

Features of Macro that can be helpful when interpreting results include:

- **Imports adjust to meet demand, but some goods are "non-tradeable". For those goods:**
  - **Investment demand is always met by sufficient supply (or the model reports that it cannot find a solution);**
  - **Export supply and supply to households and government might fall short of desired demands;**
- **Wages tend to rise with inflation, but they rise even faster when labor demand grows faster than the working-age population (and slower in the opposite case);**
- **Investment demand depends on the utilization rate of installed capital, the profitability of the sector, and a bank lending rate (which depends on inflation and the growth rate);**
- **Domestic prices are set based on costs, while foreign prices are specified externally: differences between domestic and foreign prices impact on exports and imports.**

Macro for the Amu Darya

The Macro model requires data on intermediate demand – that is, purchases by industries of the products of other industries. These are recorded in national *supply and use* tables. Furthermore, the present Activity used only publicly available data. This severely limited the number of countries for which a Macro model could be constructed. Of the riparian countries within the Amy Darya basin, only the Kyrgyz Republic provides publicly available supply and use tables. Uzbekistan prepares such tables but does not publish them.[12] Tajikistan does prepare tables, but the published versions are incomplete. Turkmenistan does not prepare such tables. Within the Syr Darya basin, Kazakhstan publishes tables. Thus, for the LEAP and WEAP analyses, which encompassed both the Amu Darya and Syr Darya basins, Macro models were prepared and calibrated for Kazakhstan and Kyrgyz Republic.

For the Kyrgyz Republic, the tables were taken from the website of the National Statistical Committee.[13] The product and sector categories in the national statistics were then aggregated to product and sector categories used for the linked LEAP-WEAP-Macro model, based on the sector and crop designations in the LEAP and WEAP models. The sector codes for the Kyrgyz Republic the same codes were used for products and services, and are provided in Table 14.

Table 14: Sector and product codes for Kyrgyz Republic

Macro code	Codes from national statistics
agfor	1
mining	4
food	5
textile	6
wood_paper	7
ENERGY_refinery	10
chem	11-13
metals	14
otherind	17, 18, 21
machinery	19
transpeqpt	20
ENERGY_elec_gas	23
otherserv	25, 37-39, 42-43, 45-46, 48, 52-56, 59, 61
construct	26
trade	27-29
transport	34
hotelrestaurant	35

The Macro model compares the rate of growth in labor demand to the growth rate of the working-age population. The working-age population was defined as those between the ages of 15-64 and was calculated using the UN historical population statistics as well as the UN middle population projection. The working-age population was calculated by combining values for the total population and for the dependency ratio for those aged 1-14 and 65+. The dependency ratio is provided every five years, so values were interpolated.

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[12] A published set of tables for Uzbekistan for 2014 was prepared in the course of a Master's thesis (available from https://www.econstor.eu/bitstream/10419/232286/1/1752051408.pdf). However, the author of the thesis stated in conversation that the tables might not be suitable for this project and attempts to calibrate the model with the data-set showed that to be the case.

[13] Tables were downloaded in Russian. They can be found at: https://stat.gov.kg/ru/publications/tablicy-resursy-ispolzovanie-tri/.

For the historical exchange rate and "world" growth rate (which drives demand for exports in the Macro model), values were calculated as a weighted average of the main trading partners for Kazakhstan and Kyrgyz Republic. Trade weights were calculated using export statistics from the World Bank's World Integrated Trade Solution (WITS) database. Exchange rates and GDP growth rates for trading partners were taken from the World Bank's World Development Indicators. Values are shown in Figure 60. For the projections, the values were assumed to rapidly converge based on historical patterns.

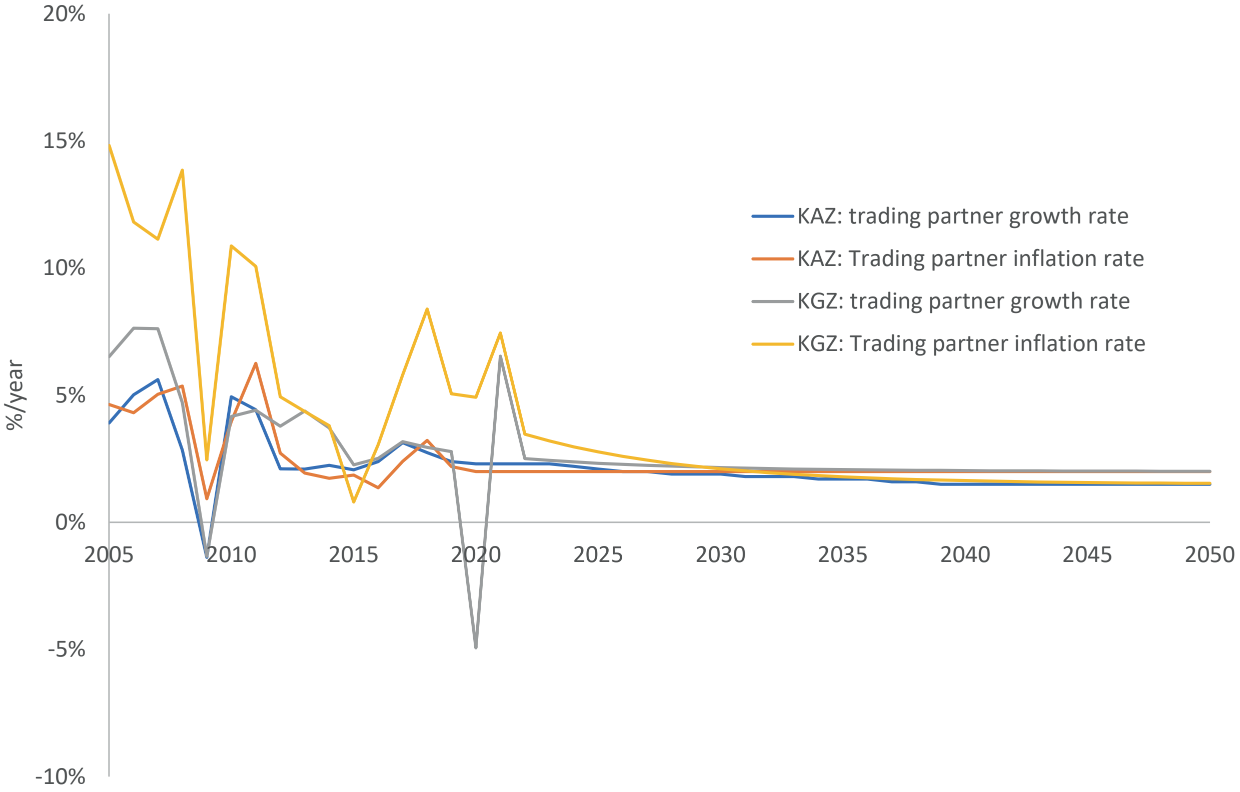

Figure 60. Trading partner growth and inflation rates for Kazakhstan and Kyrgyz Republic

World prices for most products were assumed to follow a common global inflation rate. However, prices for agricultural and energy goods were specified separately. Those for Kazakhstan are shown in Figure 61. Historical agricultural prices for seasonal, perennial, and other crops were calculated as weighted averages of prices from FAOSTAT; projected prices were held fixed at the last historical value. Prices for coal were taken from LEAP, based on national data. For petroleum products, historical prices were given by free on-board (FOB) prices taken from the US Energy Information Agency (EIA). For crude oil, prices were given by the trend for West Texas Intermediate Crude (WTI), while for refineries prices were given by New York Harbor Conventional Gasoline. For both crude oil and refineries, scenarios were provided by the International Energy Agency (IEA) World Energy Outlook *Policies* scenario.

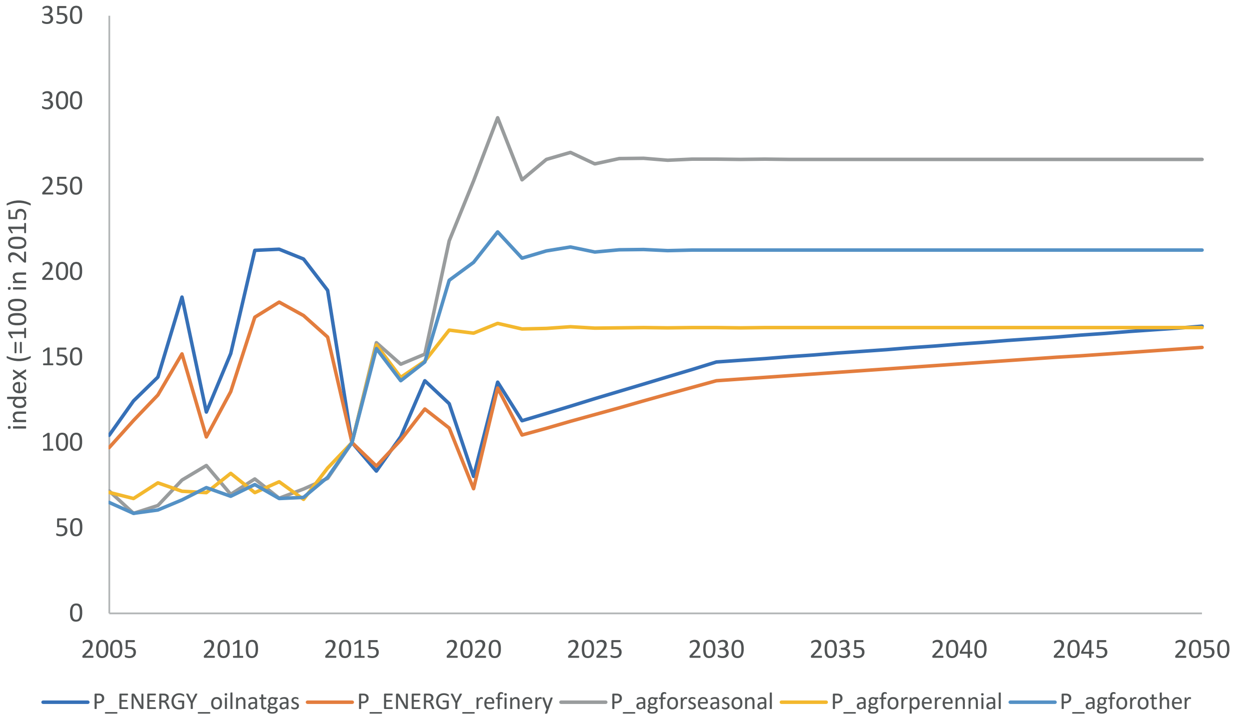

Figure 61: Prices for selected products in Kazakhstan

The Macro model was calibrated against historical data from 2012 to the latest available year. For Kazakhstan, observations were compared to model outputs for: the GDP growth rate; inflation, the nominal exchange rate, the Central Bank rate, the current account balance, and growth in labor demand. Additionally, a target value for the GDP growth rate in 2030 was taken from policy documents and further used to calibrate the model. For Kyrgyz republic most data series were incomplete, and calibration was carried out only against the GDP growth rate, together with long-run (2040) policy targets.

The link for the full Macro model (noting that is has been renamed AMES) can be found here: https://www.dropbox.com/scl/fo/8h6fuljv3lh1kiiyf1nek/ADIctIYKW3p74_awE-7rI-A?rlkey=gy3ez6ipqg5g1fp790gauhu9o&dl=0.

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