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Managing the water–energy–food nexus: Gains and losses from new water development in Amu Darya River Basin

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SUMMARY

According to the UN, the population of Central Asia will increase from its current approximately 65 million people to a well over 90 million by the end of this century. Taking this increasing population into consideration, it is impossible to project development strategies without considering three key factors in meeting the demands of a growing population: water, food and energy. Societies will have to choose, for instance, between using land and fertilizer for food production or for bio-based or renewable energy production, and between using fresh water for energy production or for irrigating crops. Thus water, food and energy are inextricably linked and must be considered together as a system. Recently, tensions among the Central Asian countries over the use of water for energy and energy production have increased with the building of Rogun Dam on the Vakhsh River, a tributary of the Amu Darya River. The dam will provide upstream Tajikistan with hydropower, while downstream countries fear it could negatively impact their irrigated agriculture. Despite recent peer reviewed literature on water resources management in Amu Darya Basin, none to date have addressed the interconnection and mutual impacts within water–energy–food systems in face of constructing the Rogun Dam. We examine two potential operation modes of the dam: *Energy Mode* (ensuring Tajikistan's hydropower needs) and *Irrigation Mode* (ensuring water for agriculture downstream). Results show that the *Energy Mode* could ensure more than double Tajikistan's energy capacity, but would reduce water availability during the growing season, resulting in an average 37% decline in agricultural benefits in downstream countries. The *Irrigation Mode* could bring a surplus in agricultural benefits to Tajikistan and Uzbekistan in addition an increasing energy benefits in Tajikistan by two fold. However, energy production in the *Irrigation Mode* would be non-optimally distributed over the seasons resulting in the most of hydropower being produced during the growing season. Neither operation mode provides optimal benefits for all the countries, emphasizing how difficult it is to actually reach a win–win scenario across the water–energy–food security nexus in transboundary river basins.

1. Introduction

1.1. Water–energy–food nexus

Food, water and energy are essential for human existence and well-being. Sustainable access to and management of these resources is a foundation for long-term economic growth and development. Challenged by the importance of efficient and balanced use of these scarce resources, several recent academic works have paid increasing attention to the concept of a water, energy and food security nexus. This concept calls for an integrated and systematic approach to address water, energy, and food security at several levels and in numerous settings (Rasul, 2014; WEF, 2011; Hoff, 2011; Hellegers et al., 2008). Understanding and identifying the linkages among these key resources and improving their use efficiency could mean a major win–win outcomes for well-being worldwide (GWSP, 2014).

The nexus approach recognizes the interlinkages between water, energy, and food production. It looks for ways to conceptualize and, if possible, quantify these linkages into a single framework to assess and manage their use that shows full respect for their connections (Hermann et al., 2012; Hussey and Pittock, 2012; Sharma and Bazaz, 2012; Bazilian et al., 2011; Scott et al., 2011; Hellegers et al., 2008). While there is an increasing amount of research trying to consider these three resources together

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Fig. 1. Map of Central Asia with the site of Rogun Dam. Data source on rivers: World Data Bank II (1980) Global river network. CIA, U.S. government. Data source on national boundaries: USGS (2001) Administrative boundaries, Global GIS Database (Reston, VA: US Geological Survey). Data source on the location of Rogun Dam: The Economist (2013).

(Rasul, 2014; Ringler et al., 2013; Gulati et al., 2013), there are few analyses done quantitatively with respect to their linkages with different policy and planning options (Bazilian et al., 2011).

The water–energy–food security nexus is particularly challenging in transboundary river basins. In such settings, each riparian country tends to maximize its own water, energy and food security. Yet, for the same reason the nexus approach is particularly relevant for transboundary settings, as it can reveal potential win–win and lose–lose situations that the actions of different countries can create for the entire region around the basin. The political character of water is also strong in transboundary basins, as the national interests of each riparian country define the outcomes of basin-wide decision-making process related to water resources development (Jägerskog et al., 2013; Earle et al., 2010).

A few previous studies stress the existence of a tight connection between the complex challenges of water, energy and food. Lee et al. (2011) presented an optimal scenario of integrated basin management in the presence of a dam. Using an example of Lake Aswan, located between Egypt and Sudan, the study showed that a move from the baseline status-quo condition to the socially optimal level will increase total basin-wide net present value by more than $500 billion (Lee et al., 2011). In addition, the study also analyzed other scenarios of cooperation. Wyrwoll (2011) demonstrated the case of the Xayaburi Project which consists of 11 mainstream dams on the Mekong River; while the project could be the "battery of Asia" (Wyrwoll, 2011) it would also have a devastating effect on food security in the region. A comprehensive study of large hydropower projects all over the world by Ansar et al. (2014) makes an interesting conclusion that "...in most countries large hydropower dams will be too costly in absolute terms and take too long to build to deliver a positive risk-adjusted return unless suitable risk management measures outlined" (Ansar et al., 2014, p. 43). Therefore, decision-makers in developing countries should explore other energy alternatives with shorter building period (Ansar et al., 2014). The most recent study by Chen et al. (2016) based on a firsthand analysis of global data on dams and socio-economic conditions, identifies the close relationship between dams and socio-economic development. They conclude that "whether dam construction should continue is no longer a question, as the need, especially in the developing countries and the LDCs, is obvious" (Chen et al., 2016, p. 27).

1.2. Amu Darya River Basin and Rogun Dam

This study investigates linkages between water, energy production and food security in the transboundary Amu Darya River Basin (ADRB). The focus is on the planned Rogun Hydropower Plant (RHP) on the second largest Amu Darya tributary i.e. Vakhsh River (Fig. 1).

The Amu Darya River is the largest river in Central Asia in terms of its length (2540 km) (Wegerich, 2008) as well as its average annual flow of 65 km^3 (Spoor and Krutov, 2003). The Basin area contains a land area of about 309,000 km^2 (Wegerich, 2008) and it is home to approximately 55 million (CIA, 2011). The mainstream is supplied by two main tributaries, the Vakhsh and Pyandj Rivers, and it inflows to the Aral Sea. The discharge regime of the Vakhsh River varies by season, with the lowest flows during winter and maximums in summer (Savchenkov et al., 1989). This phenomenon is mainly explained by melting snow and glaciers into the Vakhsh River (Konovalov, 2009).

The Amu Darya River is shared by five riparian countries – Afghanistan, Kyrgyzstan,[1] Tajikistan, Turkmenistan, and Uzbekistan. On its route from the headwaters to the Aral Sea, the river also serves as a border between Afghanistan and Tajikistan as well as between Afghanistan and Uzbekistan. There have long been heated debates among the riparian countries over the development of the Amu Darya River Basin (ADRB). Currently the debate evolves particularly around the planned Rogun Dam and around Tajikistan's right to hydropower production as well as Uzbekistan's concerns about possible negative impacts on its irrigated agriculture. There are currently few signs of willingness among the riparian countries to

[1] Kyrgyzstan supplies 2% of the total flow in the basin (SIC ICWC, 2010) and according to the "Agreement on Cooperation in Joint Management, Use and Protection of Interstate Sources of Water Resources" signed in February 1992 entitled to use only 0.6% of annual flow. Therefore, this country has not been considered in the study.

secure an agreement on the use of the Amu Darya's water resources (Kim and Indeo, 2013; Arbour, 2011).

The Rogun Dam was originally designed in the 1970s by Soviet engineers to act primarily as an irrigation reservoir that would bring new agricultural land into production in downstream areas (Azimov, 2014; World Bank, 2014). The Rogun Dam and reservoir is located about 70 km upstream of the existing Nurek Hydropower Plant (NHP) (World Bank, 2014). There are five other hydropower stations located on the Vakhsh River down from Nurek; however all are run-of-river schemes with no significant water storage capacity (World Bank, 2014). With the collapse of the former Soviet Union, original plans on Rogun's design and purpose were forgotten. The Rogun Dam is currently planned first and foremost to produce hydropower energy for Tajikistan. Nevertheless, the Rogun Dam and related reservoir has a potential to produce both agricultural and energy benefits.

Despite the ongoing political debates, there has been little peer-reviewed research on the possible economic benefits and losses that the planned Rogun Dam would bring to the riparian countries under different operation modes. While many studies analyzed and described current water resources management systems, ecological status of water bodies, joint use of water resources, as well as conflict prevention in water use in Central Asia (see Schlüter and Herrfahrdt Pähle, 2011; Wegerich, 2008; Glantz, 2005; Schlüter et al., 2005; Cai et al., 2003; Raskin et al., 1992), only a few have estimated specifically the possible economic implications of the Rogun Dam (see Bekchanov et al., 2013a, 2013b; Jalilov et al., 2013a, 2013b). In addition, in June 2014 the World Bank launched their much awaited assessment report of the Rogun Dam, investigating the technical, economic, environmental and social considerations for three possible dam heights as well as three possible energy generation capacities (World Bank, 2014). The assessment determined that the tallest Rogun Dam option of 335 m is the most suitable option to meet Tajikistan's energy needs. While Tajikistan has seen the World Bank report as a green light to commence construction of the dam, downstream Uzbekistan – which has consistently opposed the construction of the Rogun Dam – immediately expressed its disappointment and announced its unwillingness to recognize the results of the assessment (Thrilling, 2014).

1.3. Study objective

This study seeks to contribute to the current debate on the ADRB by presenting the results of the hydro-economic modeling of the basin, with a focus on different operation modes of Rogun Dam and related reservoir. The modeling results of the Rogun reservoir operation are provided in two different scenarios focusing on energy generation, *Energy Mode*, and irrigation water supply, *Irrigation Mode*. Additionally, a *Baseline* scenario is given to compare the baseline condition (with no Rogun Dam) with the two modeled scenarios. In this way, the modeling results can inform planners and policy-makers to evaluate the different management options for water, energy and agricultural development in the basin.

The remainder of the paper is organized as follows. In Section 2 we outline an analytical framework in four subsections that describe (a) use of hydro-economic models; (b) the modeling framework; (c) data used for the modeling framework; and (d) alternative modes of the dams' operation. Section 3 presents results that are divided into five subsections (a) streamflow; (b) reservoir storage and operation; (c) energy production; (d) agricultural land area; and (e) total basin-wide economic benefits. Results are discussed in Section 4 which is followed by a discussion of limitations of the study in Section 5. Finally, Section 5 also concludes and provides suggestions for future research and policy.

2. A hydro-economic model for water–energy–food interconnections in the Amu Darya River Basin

2.1. Use of hydro-economic models to guide policy

The challenge of combining the use of water, energy and food into one integrated planning and management framework is demanding and calls for the development of approaches and methods (Bazilian et al., 2011). Particularly, transboundary settings require consideration of the highly political nature of water management, as the needs of riparian countries are often conflicting. In general, many water management problems are linked to increasing water scarcity, changing climate and the lack of affordably developed new water supplies. These trends mean that by choice or necessity, priority must often be placed on improving the management of existing supplies over developing new ones. This challenge will increase the demand for techniques such as hydro-economic modeling that enable better understanding of the most beneficial allocation, use and protection of water.

Hydro-economic modeling frameworks present an integrated system where water resources can be spatially and temporally allocated under a range of management options, economic values, and policy choices. Hydro-economic modeling is a term used to describe water resource modeling studies that value some or all water uses using common a metric, usually monetary units, to compare values across time and space and among different water use categories. A guiding principle is that water demands are not a set of fixed requirements but depend on price and opportunities for substitution. They are typically represented by mathematical functions where water quantities used are distributed in different times and space due to a range of total and marginal values associated with alternative water use or conservation levels. Hydro-economic modeling often involves the use of optimization approaches to identify ways to increase the net economic benefits or other performance metrics associated with the development, purification, protection, or use of water. Integrated hydro-economic models aim to capture the complexity of interactions between water resources allocation and resulting economic performance for the purpose of informing policy choices.

2.2. The modeling framework

The model is an extension of the previous Amu Darya model (Jalilov et al., 2013a), in which the main tributary flows are allocated to various downstream water demands for beneficial use. The previous study provided empirical evidence for measures to achieve basin-wide Pareto efficiency by improving outcomes over shared transboundary waters, outcomes in which all riparian countries could be made better off by sharing the benefits of water development and allocation. In the current study, the model framework is updated to include new operation schemes by looking at country-specific benefits: under such schemes, the model maximizes the economic benefits for each country with no consideration of the total basin-wide benefits.

The model considers the economic importance of irrigated agriculture in the four basin countries i.e. Afghanistan, Tajikistan, Turkmenistan and Uzbekistan in addition to the potential for hydropower production in upstream Tajikistan. The model allocates water for energy and agricultural production over a 20-year period with a monthly time step. The model considers two cropping seasons, with the first (early planting) crop season starting in March and lasting until August and the second so-called mid-term crop starting in May (late planting) and lasting until early autumn. The model includes three key crops: cotton as strategic

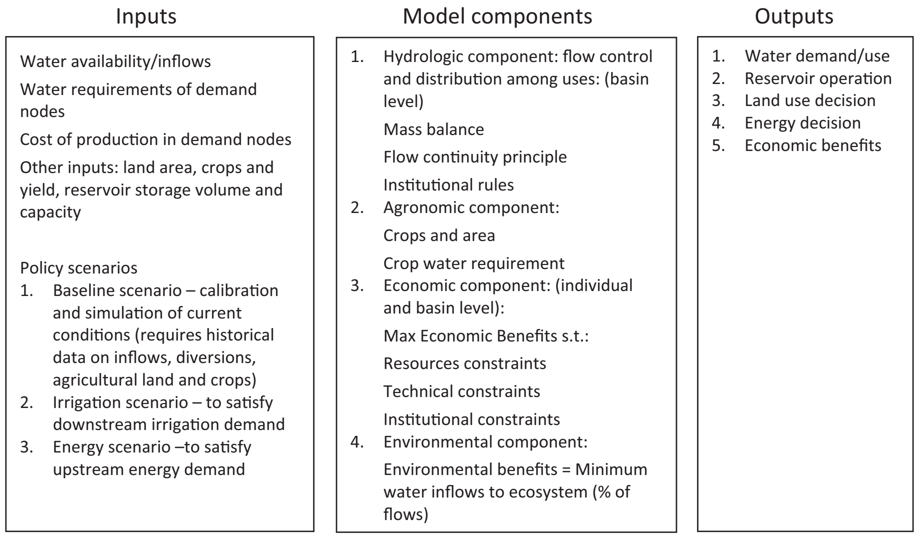

Fig. 2. Modeling framework.

cash crop, and wheat and vegetables (often potato) as crops ensuring food security for all the riparian countries.

The integrated hydro-economic river basin model consists of hydrologic, agronomic and economic elements, with special emphasis on the economic element. The modeling framework described above is summarized in Fig. 2. The nonlinear model was programmed using General Algebraic Modelling System (GAMS) language (Brooke et al., 2006). The basin scale integrated model maximizes discounted net present value (NPV)[2] across all water uses (in this case agriculture and energy), and all time periods subject to selected hydrologic and institutional constraints. Discounted net present value is equal to the sum of agricultural and energy benefits. The model allocates water among the basin's water uses, locations, and time periods to maximize net present value, subject to the described constraints.

The river basin framework is developed as a node link network, which is a representation of the spatial objects in the river basin. Nodes represent river flows, reservoir, and demand objects, and links represent the linkages between these objects (Fig. 3). Runoff from headwaters in the river basin are inflows to these nodes. Balance between flows is calculated for each node at each time period, and flow movement is calculated on the spatial connection in the river basin geometry (Appendix A).

2.3. Data

Fig. 3 shows a schematic of the Amu Darya and information on average annual water supply by source as well as the design data for the Rogun and Nurek Dams and Reservoirs. These are two major reservoirs on the Vakhsh River. The average annual water runoff in the Amu Darya River equals 65.58 km^3. The two major tributaries of the Amu Darya, the Pyanj and the Vakhsh rivers, constitute 49% and 30% of the main river's total flow, respectively.

Economic benefits of hydropower and irrigated agriculture are derived from use of water for energy and crop production. Crop water use data were used for existing cropping areas by country and combined with agricultural production details including crop prices, production costs, and crop yields (Table 1). Net agricultural income per hectare and total land in production by country, crop, and season were identified. Agricultural income per unit of land for each crop was defined as crop price multiplied by yield minus costs of production.

Discounted net farm income was summed over crops, time periods, and countries, subject to water supply and sustainability constraints described subsequently. Consistent with neoclassical price theory, reduced water quantities supplied to agricultural users decrease crop production and raise crop prices. Prices are based on previously published work that estimated price elasticities of demand and a linear demand price response at historically observed prices and production levels in the entire region. This means that the model considers all countries as a unified and linked market and allocates water to the country where benefits minus costs are highest, while respecting all constraints.

The benefits from energy production (hydropower) were measured as energy production multiplied by the constant price of energy as it is currently regulated by the Tajik government. Energy production is unknown in advance and part of the optimized model results, but as a matter of principle, it depends on head of falling water, water discharge, gravitational acceleration, and a coefficient representing the technical efficiency of turbines by which falling water is converted into power. The model of energy production closely reproduced the maximum energy capacity of Rogun Reservoir that is used in most of the recently published planning documents (The Rogunskaya Hydro Power Station, 2009).

The analysis requires a sustainable operation of the Nurek and Rogun reservoirs, defined as filling it to its maximum capacity by the last period (end of 20th year). By establishing this constraint on the terminal period's reservoir level, sustainable water supplies and use and operation modes are protected. In addition, the model was calibrated by fitting model predictions suitably close to observed historical observed values of crop production and crop land pattern in each basin country in the baseline scenario.

2.4. Two alternative modes of the Dams' operation

Our analysis looks at two alternative modes for operation of the Rogun and Nurek reservoirs, and compares them with the *Baseline Mode* i.e. the current situation with no Rogun (but with Nurek). The first reservoir operation option assumes that the both reservoirs are operated on *Energy Mode* prioritizing hydropower generation, while the second operation option assumes that the reservoirs

[2] NPV – net present value is the sum of discounted future benefits minus costs.

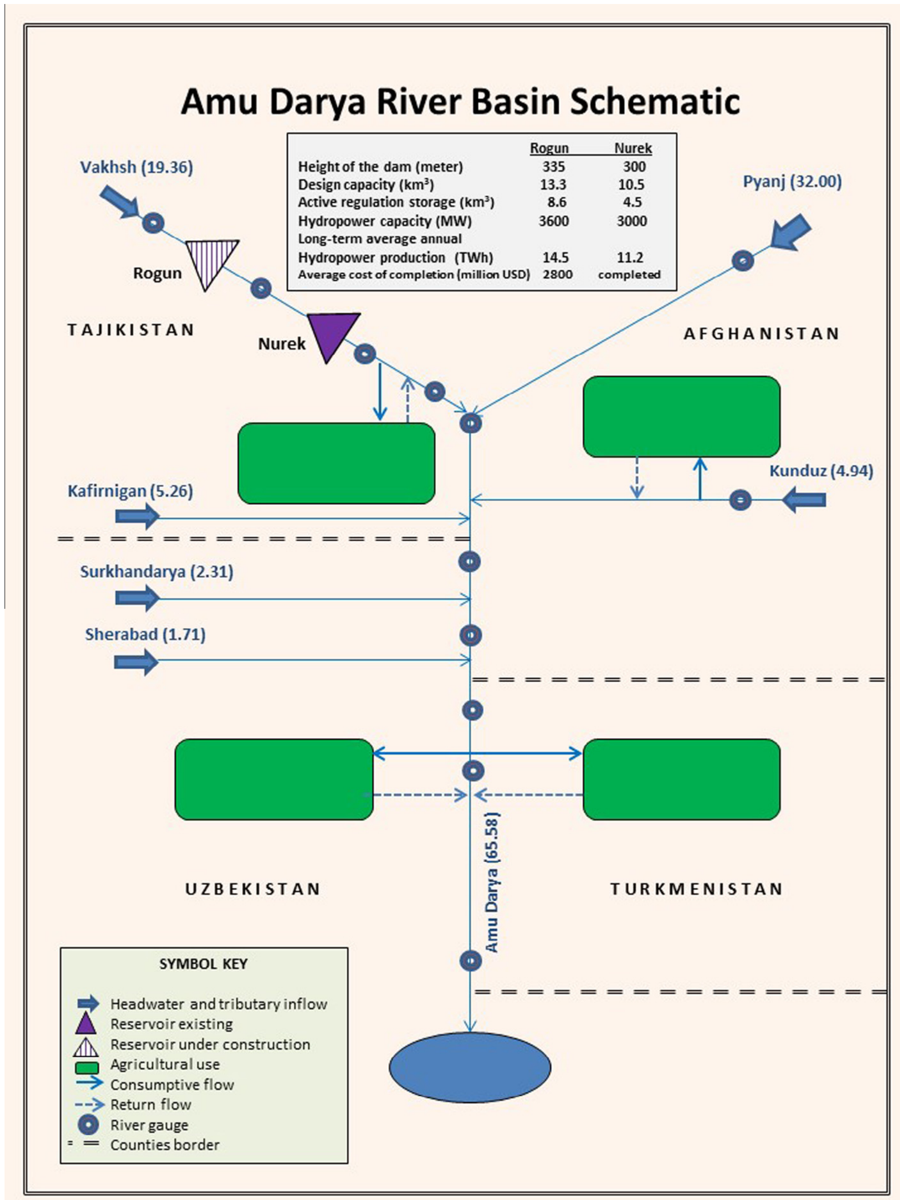

Fig. 3. Schematic of the ADRB with design characteristic of Rogun and Nurek Reservoirs (*Source:* Jalilov et al., 2013b) and average annual water flow (billion cubic meters) by tributaries of Amu Darya (*Source:* UNECE, 2007) used in the model.

operate on *Irrigation Mode*, where agriculture has the highest priority.

The two reservoir operation modes are included in the model by introducing constraints. In the *Energy Mode*, the RHP and NHP are forced to produce at least 70% of total energy requirements of Tajikistan for each month of the year (World Bank, 2012). By choosing 70%, the model forces both reservoirs to reach their maximum long-term energy production capacity. This assumption takes into account varying energy demand throughout the year. In the *Irrigation Mode*, the model is optimized so that total agricultural benefits with dams in each country must be equal or greater than without the RHP and NHP.

As water is also needed to support aquatic systems and ecology, the environmental use of water is included into the model through a constraint that ensures that at least 10% of the flow at the confluence of Vakhsh and Pyanj Rivers must flow to the Aral Sea any time of the year.

3. Results

3.1. Streamflow

Fig. 4 illustrates typical results by showing predicted streamflow on the gauge downstream of the Nurek reservoir by scenario and month averaged over a 20-year period. The reason we choose this particular gauge is because it could immediately show the impacts of upstream water fluctuations and differences in water flow between the baseline, irrigation and energy scenarios. As it can be seen from the figure, the baseline scenario is characterized by two peaks in water flowing downstream: the first peak is explained by beginning the irrigation period in downstream countries, the second peak is partly explained by the water demanded for irrigation in summer months as well as peak discharge in the Vakhsh River due to snow and glaciers melting into the Vakhsh River (Konovalov, 2009). Flow in the energy scenario is the most

Table 1
Agricultural data by country and crop. *Source:* World Bank (2003).

Country	Crop	Yield (tons/ha)	Cost ($US/ha)	Water requirements (m^3/ha per year)	Total land area in production within Amu Darya Basin (million ha)
Tajikistan	cotton	1.8	444	12	0.5
	wheat	1.5	168	8	
	vegetable	12	500	12	
Afghanistan	cotton	1.8	444	12	0.4
	wheat	1.6	165	8	
	potato	12	503	12	
Uzbekistan	cotton	2.3	390	14	2.3
	wheat	1.5	283	6	
	vegetable	11	702	11	
Turkmenistan	cotton	2.2	392	14	1.1
	wheat	1.5	283	6	
	vegetable	11	702	11	

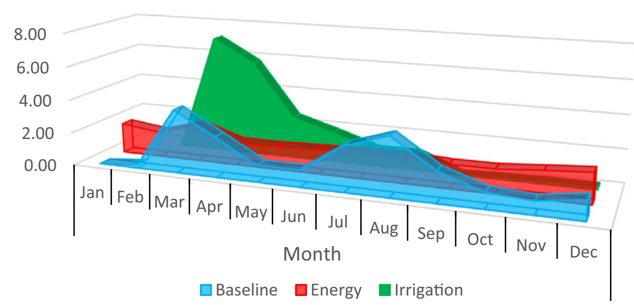

Fig. 4. Predicted streamflow on the gauge down the Nurek reservoir by scenarios and months, averaged over a 20-year period.

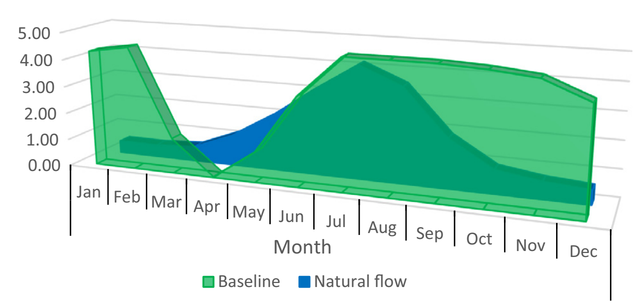

Fig. 5. Fluctuation of the Nurek reservoir storage volume by months in baseline scenario, averaged over a 20-year period.

evenly distributed across the months due to fact that there is a nearly constant energy demand throughout the year in Tajikistan. However, a closer looks shows that energy demand is higher in winter months and lower in summer months. Another picture is presented in the irrigation scenario. Both reservoirs working for the sake of agriculture downstream accumulate water in fall and winter months and release it starting in the spring. By doing this both reservoirs could actually help to bring new lands into production and thus increase agricultural benefits downstream. The important message of the figure is that both modeled scenarios are considerably different from the baseline scenario and also significantly differ between each other.

3.2. Reservoir storage and operation

With a capacity of 13.3 km^3 for storage and an average annual runoff from the Vakhsh River of 20 km^3, it is possible to store about two-thirds of the river's annual flow into the Rogun reservoir. Adding the Nurek reservoir to this equation could make the picture even worse as both reservoirs together could store the entire annual runoff of the Vakhsh River. Taking into account that the Vakhsh River contributes about one third of the total discharge into the Amu Darya River, it is clear that the proposed Rogun reservoir together with the existing Nurek reservoir could potentially regulate a very high percentage of the water used for the basin's agricultural production.

Fig. 5 shows fluctuation of the Nurek reservoir's monthly storage volume averaged over 20 years in the baseline scenario, indicating a typical operation of the reservoir in meeting irrigation

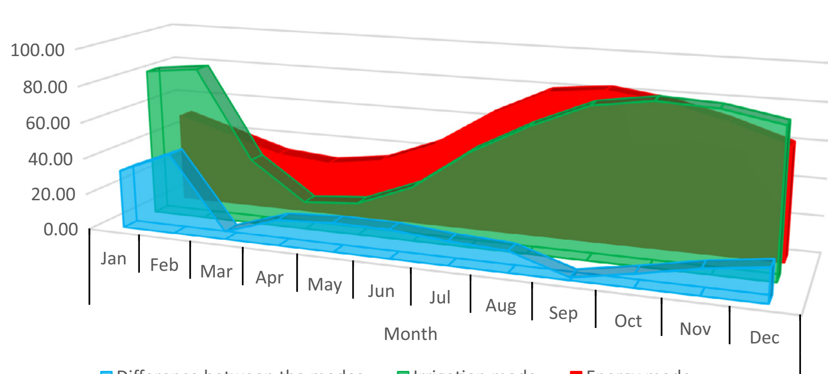

Fig. 6. Fluctuation of the Rogun reservoir storage volume by months in Energy and Irrigation scenarios, averaged over a 20-year period (in percentage of the maximum storage capacity).

water needs downstream. The baseline scenario was modeled to reproduce a historical irrigated area in downstream countries. Normally, the Nurek reservoir would release water in spring and summer to satisfy irrigation water demands of downstream agriculture and accumulate water in the high runoff period of summer and throughout the fall and winter months. However, it does not mean this scenario occurs currently due to ongoing disputes over the allocation of water resources in the Amu Darya Basin.

Fig. 6 shows the Rogun reservoir storage fluctuations in percentage of the maximum storage capacity by months in two modeled scenarios: *Energy* and *Irrigation*. While operating under the *Energy Mode*, the Rogun Reservoir stores water during late summer and early fall months when river flow is the greatest and then releases water to generate electricity during winter and spring months when the energy demand is the highest (World Bank, 2012). This is clearly visible in Fig. 6, where under the *Energy Mode* the reservoir starts to store water gradually from June onwards with the reservoir storage being the greatest in September. Then from September onwards, water flows are released to generate hydropower.

Under *Irrigation Mode*, the reservoir operation is considerably different with a storage peak falling in February. Starting from March, water is released as the farming season begins. Decline in water release is observed from June onwards when the major irrigation season ends and harvesting season begins, thus reducing the demand for irrigation water. From then onwards the flow from the reservoir is minimal and the reservoir storage thus increases slowly, hitting its peak again in February before the next planting season starts.

Overall, Fig. 6 depicts a clear difference in Rogun reservoir operation under the *Energy Mode* and the *Irrigation Mode*. Moreover, it displays an obvious conflict of interests between food and energy production in the Amu Darya River Basin. While food production needs water to be stored in fall and winter, energy production needs to store water during the summer. High demand for electricity during the winter period forces the reservoir to release water through turbines to generate energy in the *Energy Mode*. Similarly, irrigation water is in high demand during the spring-summer period forcing the reservoir to store water during the winter period when water flow in the river is minimal.

The blue[3] area in Fig. 6 shows the difference in water volume (in percentage of the maximum storage capacity) between the modes of the reservoir operation noticed for the particular month. Depending on the certain month and the reservoir operation mode this indirectly indicates volume of water being stored in the Rogun as well as delivery levels to downstream users in the particular month. As might be suspected, this amount of water is the major source for disputes between *Irrigation* and *Energy* scenarios in the reservoir operation.

Storage fluctuation of the Nurek reservoir in percentage of the maximum storage capacity by months in two scenarios is shown in Fig. 7. The *Irrigation Mode* for the Nurek reservoir has a similar pattern to the Rogun reservoir operation in the same mode – accumulating water in winter months and releasing it in summer and fall partly because of irrigation demands and partly because of peak summer runoff allows for the generation of electricity and additional energy benefits. However, the situation is different in the *Energy Mode* which shows almost no fluctuations of the reservoir storage. This occurs in order to satisfy energy demand in Tajikistan which is distributed more or less evenly throughout the months of the year (World Bank, 2012). Energy production is given more in details in the next subsection.

[3] For interpretation of color in Figs. 6 and 7 , the reader is referred to the web version of this article.

The blue area in Fig. 7 shows the difference in water volume (in percentage of the maximum storage capacity) between the modes of the reservoir operation noticed for the particular month. Depending on the month and the reservoir operation mode this indirectly indicates the volume of water being stored in the Nurek reservoir as well as downstream deliveries by month.

We should mention that Figs. 6 and 7 show fluctuations in reservoir storage level averaged over 20-year period and shouldn't be interpreted as changes of reservoir storage capacity which is fixed and cannot be changed.

3.3. Energy production

Figs. 8 and 9 show model estimated monthly energy production by the Rogun and Nurek reservoirs under both the *Energy Mode* and the *Irrigation Mode*. In the *Energy Mode*, both reservoirs are required to produce at least 70% of the electricity needed in Tajikistan during different months (World Bank, 2012). According to that source the demand for electricity in Tajikistan is relatively evenly distributed across all the months with exception from November until March, when energy demand is high. As Tajikistan's energy demand is higher in winter months, the reservoirs store high river flow during the summer and release it to satisfy high demand for energy in winter. This is visible in Figs. 8 and 9, where the energy production is higher in the winter period on compared to the summer period. The peak of energy production falls in March as this month's demand for energy is higher than demand in February (as seen in the Nurek operation). This can be seen as a win–win case for Tajikistan, as it would increase the country's energy security and through possible energy export also bring in additional revenue to the country.

It should be mentioned that under the *Irrigation Mode* energy production of both reservoirs has sharp fluctuations as the reservoir follows agriculture needs for water. As a result, the most energy is produced between February–August and understandably little energy produced in winter when water has to be stored for the next irrigation period. In the *Irrigation Mode* the reservoirs operation reflects the irrigation water needs of agriculture. The *Irrigation Mode* presumes that the most energy is produced in March–August. The energy production under *Irrigation Mode* presents then a kind of win–lose case for Tajikistan. While it could generate a large surplus of electricity in six months (March to August), it could also suffer from the insufficient energy supply in September through December and almost no energy supply in January and February when the energy demand is the highest.

3.4. Agricultural land area

The different reservoir operation modes will naturally impact the potential agricultural land area due to changes in the water availability in the Amu Darya River, which is the major source for irrigation water within the riparian countries (Spoor and Krutov, 2003). Historically, Central Asia's agricultural land area increased with irrigation expansion in the 1970s and 1980s (i.e. the Soviet era), leading also to the widely-publicized loss of much of the Aral Sea. Thus, the most limiting factor for agricultural production is the availability of water.

Table 2 summarizes the results of total agricultural area under production by country, crop, and scenario. The table presents two important messages: no country except Afghanistan could experience a potential reduction in agricultural area under the *Energy Mode* due to reduced availability of water for irrigation. However, the situation is different when one looks at crop distribution: Uzbekistan and Turkmenistan would have to decrease land under cotton production, which the most water-intensive crop among the three presented here and needs to be planted as a first crop.

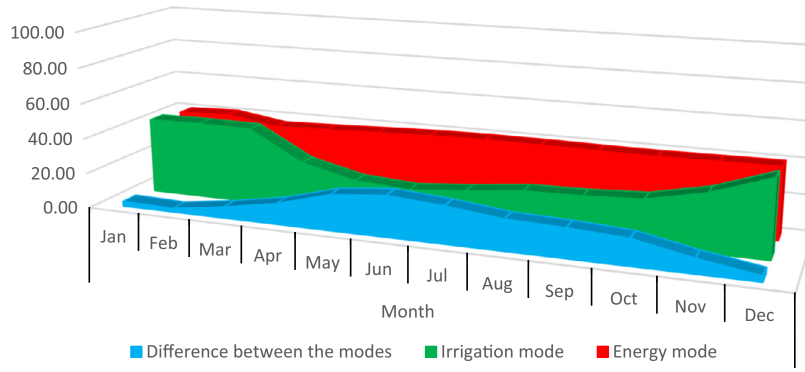

Fig. 7. Fluctuation of the Nurek reservoir storage volume by months in Energy and Irrigation scenarios, averaged over a 20-year period (in percentage of the maximum storage capacity).

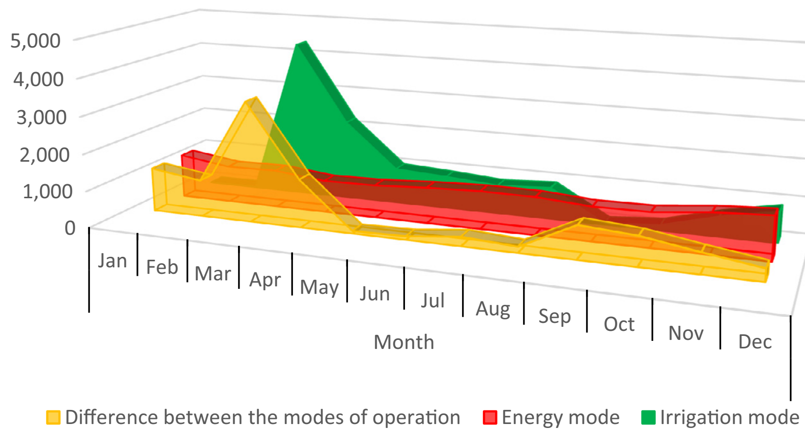

Fig. 8. Rogun reservoir energy production by scenarios and months, averaged over a 20-year period.

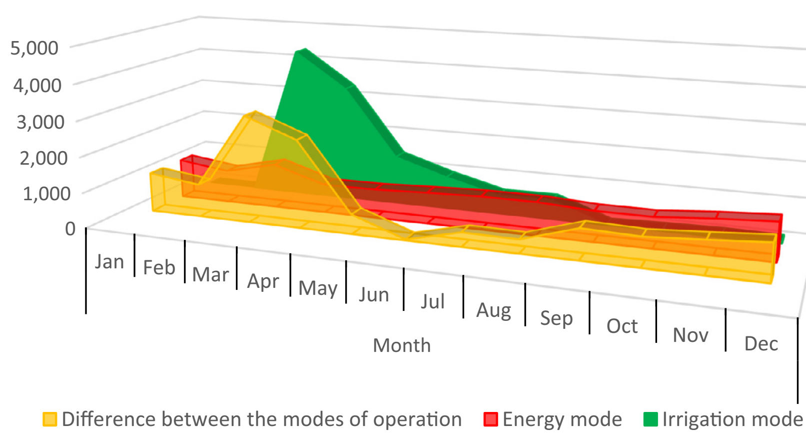

Fig. 9. Nurek reservoir energy production by scenarios and months, averaged over a 20-year period.

In exchange, the model calls for an increase in land under production for wheat, as this crop is less water intensive and has the lowest production cost compared to the other two crops and could be planted later in the season when water is more readily available.

Conversely, the *Irrigation Mode* of the Reservoir operation brings more potential, as it allows to develop new land (except for Afghanistan) as the Rogun and Nurek reservoirs act as multiyear water storage. The greatest potential for increase in agricultural land area would be in Turkmenistan and Uzbekistan (1.4 and 1.2 times, correspondingly), but also Tajikistan could increase its agricultural area 0.5 times under this scenario. In other words, if the Rogun Reservoir is operated under the *Irrigation Mode*, it could potentially store water during high flows and release it in low flow periods, bringing more land into production and accordingly more benefits to all the countries in the basin.

There is no land being cultivated for vegetables in Afghanistan, Uzbekistan or Turkmenistan as the model was calibrated to reproduce total irrigated land area in those countries in a *Baseline* scenario, and because of the fact that considerably high profitability of cotton and wheat in the model allocated water to grow these crops in both the *Irrigation* and *Energy* scenarios.

The subsequent changes in agricultural benefits of the particular country are presented in the next subsection.

Table 2
The agricultural land area (millions of ha/year) by country and reservoir operation mode, averaged over 20 years.

Country	Scenario	Crops			Total over crops
		Cotton	Wheat	Vegetables	
Tajikistan	Baseline	0.00	0.15	0.10	0.25
	Irrigation	0.00	0.28	0.11	0.39
	Energy	0.00	0.18	0.06	0.24
Afghanistan	Baseline	0.00	0.13	0.00	0.13
	Irrigation	0.00	0.12	0.00	0.12
	Energy	0.00	0.07	0.00	0.07
Uzbekistan	Baseline	0.80	0.32	0.00	1.12
	Irrigation	0.89	1.59	0.00	2.48
	Energy	0.44	0.68	0.00	1.12
Turkmenistan	Baseline	0.24	0.08	0.00	0.32
	Irrigation	0.24	0.55	0.00	0.79
	Energy	0.14	0.19	0.00	0.33

3.5. Total basin-wide economic benefits

Total basin-wide economic benefits were calculated as a sum of agricultural and energy benefits for each country. However, instead of showing absolute numbers representing actual monetary benefits we decided to assign the baseline scenario as a base level and *Irrigation* and *Energy* scenarios as a percentage change compared to the *Baseline* scenario. Therefore, Table 3 shows percentage changes of agricultural, energy and total benefits compared with the *Baseline* scenario by country over a 20-year period. The table presents two main messages: (1) Reservoirs operated in the *Irrigation Mode* could bring agricultural benefits to Tajikistan and Uzbekistan and almost double total basin-wide economic benefits; (2) Reservoirs operated in *Energy Mode* could bring energy benefits to Tajikistan, agricultural losses for all riparian countries, including Tajikistan, but double total basin-wide benefits as well. This happens by securing significant energy benefits for Tajikistan, much of which could see export to the other basin countries.

Reservoirs working in the *Irrigation Mode* present an opportunity for Tajikistan to increase agricultural and energy benefits and Uzbekistan to increase agricultural benefits. For example, Tajikistan could secure a growth in benefits of 120% and Uzbekistan could secure a growth in benefits of 10%. If the Rogun Reservoir is managed in *Energy Mode*, Tajikistan could secure even higher benefits by 128%, but the remaining countries would shoulder a considerable decline in agricultural benefits.

4. Discussion

The results of this investigation showcase the importance of improved information on the economic impacts of future operation modes of the Rogun Reservoir for the various countries influenced by its operation in the Amu Darya River Basin. Both reservoir operation modes investigated present significant consequences for all of the riparian countries in the region. Operation in the *Energy Mode* causes reduction of water supply downstream in summer and as a result significant losses of agricultural benefits in Afghanistan, Uzbekistan and Turkmenistan. In contrast, operation in the *Irrigation Mode* would leave Tajikistan with little electricity supply from the reservoirs in their highest power demand period. Our results also indicate that in the *Irrigation Mode* additional benefits could be acquired by downstream Uzbekistan only. This is a consequence of the upstream location of Uzbekistan and the possibility of it using irrigation water prior to its downstream neighbor.

While hydropower production does not impact the quantity of water (with the exception of reservoir evaporation water losses), it strongly impacts the timing of river flows as the timing of water releases from the reservoir is dictated by the energy demand. Such flow changes may lead to conflicts between upstream hydropower generation and downstream water users, including irrigation as well as ecosystem needs. Water needs for energy production and irrigated agriculture are seasonally very different.

Tajikistan's increased energy security would come at the expense of downstream countries' irrigation sectors. Under the *Energy Mode*, Tajikistan would release water during winter to meet its energy demand, but Uzbekistan and Turkmenistan need water during the summer to ensure the sustainability of their large irrigated agriculture. As a result, large areas of downstream cotton plantations could be lost due to decreased water availability during the peak irrigation season. When taking into account that the irrigation sector plays a leading part in the national economies of both Uzbekistan and Turkmenistan and a high percentage of the population is engaged in agriculture, this could have major economic and social consequences.

Nevertheless, results from the *Irrigation Mode* show that the reservoirs could be operated so that they bring major agricultural benefits and potentially even increase the agricultural land area in upstream Tajikistan and downstream Uzbekistan. Under this management, the Rogun Reservoir acts as a multiyear water storage regulator, thus helping downstream countries adapt to future droughts or floods. In this way, the Rogun Dam could have a major positive impact on the national economies, food security and economic development of the two downstream countries.

Table 3
Total discounted economic benefits (over 20 years) by country and reservoir operation mode in ratios to the baseline scenario.

Country	Policy	Agricultural benefits	Energy benefits	Total benefits
Tajikistan	Baseline – Nurek	100	100	100
	Both dams – Irrigation	8	+124	+120
	Both dams – Energy	−16	+134	+128
Afghanistan	Baseline – Nurek	100		100
	Both dams – Irrigation	0		0
	Both dams – Energy	−26		−26
Uzbekistan	Baseline – Nurek	100		100
	Both dams – Irrigation	10		+10
	Both dams – Energy	−25		−25
Turkmenistan	Baseline – Nurek	100		100
	Both dams – Irrigation	0		0
	Both dams – Energy	−23		−23
Total over countries	Baseline – Nurek	100		100
	Both dams – Irrigation	8		+80
	Both dams – Energy	−24		+75

Operating both dams in the *Irrigation Mode* would not meet timing of energy demand; however, Tajikistan will still secure significant levels of energy benefit. While the dam would still produce annually high levels of energy, the timing of energy production would be dictated by agriculture and not energy demand. As a result, Tajikistan risks continuing to suffer from energy shortage during several months while having energy surplus in other months. The Rogun Dam case in Central Asia is not a unique – other countries face similar conditions and can tell similar stories about their water managers and people. For instance, the Grand Ethiopian Renaissance Dam (GERD) on the Nile River is the source of conflict between upstream Ethiopia and downstream Egypt. Similar to Tajikistan, Ethiopia needs energy for its economic development and wants to build the GERD, but Egypt opposes Ethiopian plans because of negative impacts on its long-established agriculture. The Xayaburi Dam on the Mekong River is supposed to bring considerable energy benefits to Laos (LPDR), although the downstream countries of Thailand, Cambodia and Vietnam oppose the dam construction based on its detrimental impacts on their food security, driven by fishery production.

Without explicit trade in food, water, and power, in which overall efficiency gains of basin-wide optimization are shared among countries, there are few easy solutions. Each country seeks to ensure its own national interests, whether it is food or energy production. However, there is another solution not investigated in this study but which could merit future analysis. One option is operate each dam differently, for instance the Rogun could operate in the *Energy Mode* while Nurek operates in the *Irrigation Mode*. By enacting this approach, Tajikistan would still ensure its seasonal electricity demand and downstream countries would secure water needed for its crop irrigation. This could be an opportunity for all riparian countries to reach a benefit sharing Pareto Improvement in the Basin.

While the current situation is difficult to resolve we believe that the Basin countries could negotiate a settlement over equitable benefit sharing mechanisms that implement some form of redistribution or compensation. Naturally, the form of this redistribution or compensation is highly situational and site specific, but could involve monetary transfers, granting of rights to use water, financing of investments, or the provision of non-related goods and services (Sadoff and Grey, 2002). As Sadoff and Grey (2002) note "while some benefits are difficult to share or compensate, in general the optimization of benefits should be more robust and more flexible than the optimization of physical water resources, because benefits tend to be more easily monetized and compensated and they have less political and psychological significance" (Sadoff and Grey, 2002, p. 397). The scope of discussed benefits is also subject to negotiations. The larger the scope of measures over which negotiation can occur, the more likely the riparians will be able to find arrangements of benefits that are mutually acceptable.

There are cases of successful implementation of benefit sharing concepts in various parts of the world. Canada and the United States reached agreement on benefit sharing mechanisms and concluded the Columbia River Treaty in 1964 (Tarlock and Wouters, 2007). Guinea, Mauritania, Mali, and Senegal, all of which share the Senegal River Basin, agreed in 1972 to share the benefits derived from water use, such as irrigation, hydropower generation, and inland navigation (Alam et al., 2009; Haas, 2009). An example of the Orange-Senqu River Basin, shared by South Africa, Lesotho, Botswana and Namibia, shows a case where a downstream country built a dam upstream to increase aggregate net benefits, so both the downstream and upstream countries can share the project's benefits, rather than pursuing a unilateral alternative. (Hensengerth et al., 2012; Yu, 2011).

Based on the above-mentioned successful cases we could suggest to study the applicability of benefit sharing concepts related to the Amu Darya basin. The *Energy Mode* scenario assumes a 128% increase in Tajikistan's total benefits. Detailed calculation is needed to check whether this surplus of benefits would allow Tajikistan to compensate losses of other riparian countries and still be better-off. By doing this Tajikistan also may seemingly get consent of downstream countries that object to building the Rogun Dam. Another option could be a restoration of benefit sharing schemes used in the former Soviet period. The scheme is based on the principle – water was provided for the downstream countries in vegetation time, so upstream countries had to store water in their reservoirs in winter and release it in summer. In exchange, downstream countries were obliged to provide upstream countries with energy resources (natural gas, oil, coal) in the winter months. This scenario worked well until the emergence of newly independent countries emerging out of the former Soviet Union, who did not want to follow previous Soviet agreements. Of course, at first each involved country must agree to such a scheme and new more detailed calculations should be made. It could turn out that this scheme would not be acceptable from a benefits and costs point of view under the current situation.

The novelty of this study in comparison with the previous studies on the Rogun Dam (Bekchanov et al., 2013b; Jalilov et al., 2013a, 2013b) is that it aims to balance contradiction (economic gains and losses) between energy mode and irrigation mode in different dams by multi-objective optimization and decision making methods. While those studies conclude that the Rogun Reservoir has a modest impact on downstream irrigation if the reservoir is operated to maximize basin-wide benefits, our investigation in the current work shows more strongly the differences among the riparian countries in potential economic benefits and losses under a range of operation modes. This fundamental difference becomes more clear when pointing out those previous studies made assumptions about regional cooperation that would lead to optimal allocation of basin-wide economic benefits. Our investigation used a different and perhaps more realistic view where each country focuses solely on its own interests and tries to maximize the national benefits derived from the Rogun and Nurek Dams.

5. Limitations and conclusions

This study has limitations, related both to data and approach. The analysis is based on simple datasets that are widely available. Hydrological data from the area are weak as a consequence of inadequate hydrometric networks, and there is also little consistently collected agricultural data available for crop production, cost, yields, or crop water use. Our study has therefore required major assumptions and simplifications on the cropped area, crop mix, river flows, and crop water use. Due to lack of reliable data on aquifers, the study also excluded groundwater use for irrigation. In addition, the model is based on the assumption that there are institutions and markets that efficiently use and allocate land, water, crop and energy. The modeling framework faces limitations as well. For example, the model constraints are simplifications. Yet, despite these limitations the study has demonstrated how different scenarios regarding the Rogun Dam can produce different economic benefits for the riparian countries.

This article has presented an analysis of possible future operation modes of the controversial Rogun Dam, located in the major tributary of the Amu Darya River. The hydro-economic modeling results of two operation modes – *Energy Mode* and *Irrigation Mode* – indicate that the Dam can be operated in different ways, leading to dramatically differing benefits and losses for the riparian countries. However, neither operation mode provides optimized benefits for all the countries, emphasizing how difficult it is to actually reach win–win situations across a water–energy–food security nexus in large river basins.

The mission of this investigation was to examine the possibilities to develop the water resources in the Amu Darya River Basin so that it would maximize food, energy – and economy-related benefits for all riparian countries while minimizing the losses to these sectors as well as to the environment. The planned Rogun Dam is, due to its size and importance, was the focus of our work. While this study shows the benefits of differing operation modes of the Rogun Dam, it does not seek to provide an operational solution for this challenging and politically sensitive case. Yet, we would like to see our results open and facilitate the discussion about the sustainable water resources development in the region.

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Appendix A

The model and its documentation were originally developed for application to the Amu Darya Basin in the Central Asia. However, it is adaptable to the hydrology, water infrastructure development, land use patterns, economics, and institutions of any basin.

The essential principle of the hydrology component of model is mass balance – for surface flow, water diversions and water depletions for use in irrigated agriculture. Important variables tracked include water storage capacity, crop mix, land in production, and farm income associated with various scales of water storage under conditions of various water supply scenarios from base and drought. The model structure is defined below using the GAMS notation, described by the vendor at gams.com.

A.1. Sets

Sets are the dimensions over which the storage scaling model is defined. A similar structure could be used for reservoir capacity analysis anywhere new water storage is planned. The following sets and set elements are used.

i	Flows	/inflow, river, divert, use, return, release/
u	Stocks	/reservoir/
t	Months	/Jan–Dec/
y	Years	/1–20/
j	crop	/cotton, wheat, vegetables/
k	crop season	/first, second/
n	water supply scenario	/base, dry/
p	Policy	/wo_dam, wi_dam1, wi_dam2, wi_dam3/
s	Region countries	/Afghanistan, Tajikistan, Turkmenistan, Uzbekistan/

A.2. Data

Some of the following parameters (data) terms end in _p to distinguish parameters (unknown terms) from unknown variables. Parameters are:

Bu (*divert*, *use*)	defines consumptive use as a percent of diversion
Br (*divert*, *return*)	defines surface return flow as a percent of diversion
BLV (*rel*, *u*)	links reservoir releases to downstream flows
source (*inflow*,*y*, *t*, *n*, *p*)	annual basin inflows at headwaters in scenario (cubic km per month)
yield_p (*use*, *j*, *k*)	crop yield (tons per hectare)
cost_p (*use*, *j*, *k*)	crop cost of production (USD per ton)
price_elast (*j*)	price elasticity of demand
P_p (*j*)	observed crop price (USD per ton)
Bu_p (*i*, *j*, *t*)	crop water demand per hectare (divert + use + return) per month
Capacity (*res*, *p*)	reservoir maximum capacity by stages
Z0 (*res*)	initial reservoir level at stock node
h0_p (*res*, *y*, *t*, *n*, *p*)	dam's maximum height in stages
ID_ru (*return*, *use*)	identity matrix connects return nodes to use nodes
ID_du (*divert*, *use*)	identify matrix connects divert nodes to use nodes
Landrhs_p (*use*)	Irrigated land area by countries (million hectares)
hydro_price (*res*, *t*)	price of hydropower (constant USD per kW h)

A.3. Variables (unknowns)

Some of unknown variable ends in _v, to distinguish variables from known data. The model solves for the optimal value of each of these variables, for which the goal is to maximize several alternative aggregations of total basin net economic benefits while respecting key constraints.

A.3.1. Positive variables

Z_v (*res*, *y*, *t*, *n*, *p*)	reservoir water stocks
reservoirs_h_v (*res*, *y*, *t*, *n*, *p*)	reservoirs height in each month
supply_v (*inflow*, *y*, *t*, *n*, *p*)	supplies
hectares_v (*use*, *j*, *k*, *y*, *t*, *n*, *p*)	area under each crop in each country in time
land_v (*use*, *y*, *t*, *n*, *p*)	land in production
production_v (*use*, *y*, *t*, *n*, *p*)	crop produced in each country
T_production_v (*j*, *k*, *y*, *t*, *n*, *p*)	crop produced
energy_prod_v (*res*, *y*, *t*, *n*, *p*)	energy production
energy_ben_v (*res*, *y*, *t*, *n*, *p*)	energy production benefits in Rogun in each month

A.3.2. Free variables

X_v (i, y, t, n, p)	water flows (inflow, river, divert, use, return, release)
Con_surp_v (j, y, t, n, p)	consumer surplus
ag_ben_v (use, y, t, n, p)	net income over crops by node and period
tot_agben_v (use, n, p)	net agricultural benefits by country
con_surpl_v (j, y, t, n, p)	consumer surplus
$Totben\_v$ (n, p)	total benefits

A.4. Equations

A.4.1. Hydrology

Hydrology respects mass balance, both for surface flow interactions and reservoir levels. The hydrology uses mass balance principles to account for headwater flows, river flows, reservoir levels, water from surface applied to various uses, and the impact of surface flows on current and future reservoir storage levels.

A.4.1.1. Headwater runoff

$$X\_v(inflow, y, t, n, p) = source(inflow, y, t, n, p) \tag{1}$$

A.4.1.2. River flow

$$\begin{aligned} X\_v(river, y, t, n, p) = {} & sum(inflow, Bv(inflow, river) \\ & * X\_v(inflow, y, t, n, p)) \\ & + sum(riverp, Bv(riverp, river) \\ & * X\_v(riverp, y, t, n, p)) \\ & + sum(divert, Bv(divert, river) \\ & * X\_v(divert, y, t, n, p)) \\ & + sum(return, Bv(return, river) \\ & * X\_v(return, y, t, n, p)) \\ & + sum(rel, Bv(rel, river) \\ & * X\_v(rel, y, t, n, p)) \end{aligned} \tag{2}$$

A.4.1.3. Water diverted

$$\begin{aligned} X\_v(divert, y, t, n, p) = {} & sum((j, k), Bu\_p(divert, j, t) \\ & * sum(use, ID\_du(divert, use) \\ & * hectares\_v(use, j, k, y, t, n, p))) \end{aligned} \tag{3}$$

A.4.1.4. Gross surface returns to river

$$\begin{aligned} X\_v(return, y, t, n, p) = {} & sum((j, k), Bu\_p(return, j, t) \\ & * sum(use, ID\_ru(return, use) \\ & * hectares\_v(use, j, k, y, t, n, p))) \end{aligned} \tag{4}$$

A.4.1.5. Water consumed: Any water use node's consumptive use is an empirically-determined proportion of total water applied. For irrigation, consumptive is the quantity of water lost through plant evapotranspiration (ET) to any future use in the system. For agricultural nodes, water use is measured as:

$$\begin{aligned} X\_v(use, y, t, n, p) = {} & sum((j, k), Bu\_p(use, j, t) \\ & * hectares\_v(use, j, k, y, t, n, p) \end{aligned} \tag{5}$$

For hydropower generation use, consumptive use is the quantity of water flowing through turbines. However, that water quantity could be reused for irrigation if it fits right time. That water use generates energy, which cannot be negative. It is measured as:

$$\begin{aligned} Z\_v(res, y, t, n, p) = {} & Z0(res) - sum(rel, BLV(rel, res) \\ & * X\_v(rel, y, t, n, p)) \end{aligned} \tag{6}$$

Energy production is total water flow to generate energy in month of year, by scenario and policy. Remaining coefficients are: g -gravitational constant ($g = 9.8$ N/kg); E, Efficiency, which can vary from 0 to 1, and transformation coefficients.

$$\begin{aligned} Energy\_prod\_e(res, y, t, n, p) = {} & X\_v(y, t, n, p) * 9.8 * 0.75 * 24 \\ & * (365/12) \end{aligned} \tag{7}$$

A.4.2. Reservoir storage

Reservoir contents are:

$$\begin{aligned} & Z\_v(res, y, t, n, p) = sum((y2, t2), \\ & Z(res, y2, t2, n, p) - sum(rel, BLV(rel, res) * X\_v(rel, y, t, n, p) \end{aligned} \tag{8}$$

Electric power comes from building a Reservoir on a river that has a large drop in elevation. There are few hydroelectric plants in flat places. The dam stores water behind it in the reservoir, and a higher storage volume of water in the reservoir means that the water falls a greater distance and reaches a greater velocity when passing through the turbines. The turbine converts the energy of flowing water into mechanical energy. The hydroelectric generator converts this mechanical energy into electricity. The hydraulic head for the reservoir's dam in the month of year, scenario and policy was empirically estimated to fit conditions for the Rogun reservoir:

$$\begin{aligned} Reservoir\_h(res, y, t, n, p) = {} & 3698.10229 - 3451.26986 \\ & * \left(\frac{1}{Z\_v(res, y, t, n, p) * *0.01} \right) \end{aligned} \tag{9}$$

The idea of these coefficients is: on the basis of known limited data on Rogun reservoir's water volume which depends on the height of the dam to find nonlinear relation between storage volume and the head of the dam, so we could exactly predict what would be head having certain water volume. Contents of the reservoir in the initial period (*0*), $Z0$:

$$Z0 = 0 \tag{10}$$

The upper bound on the reservoir's contents is defined as:

$$Zmax = C \tag{11}$$

This equation guarantees that the reservoir's level never exceeds its capacity. Policies that would change a reservoir's capacity, such as dredging or adding to a dam's height, are simulated by altering the value of C.

A.5. Land use

Land use patterns affect the demand for water. For irrigated agriculture, total land in production is expressed as:

$$\begin{aligned} & Sum((j, k), hectares\_v(use, j, k, y, t, n, p)) \\ & = land\_v(use, y, t, n, p) \end{aligned} \tag{12}$$

This states that irrigated land in production by node, crop, season, and time, summed over crops and seasons cannot exceed available land (RHS) by node, time period for any given scenario and policy. In most dry rural regions of the world, like the Amu Darya Basin, water is often more limiting than land. While we used the maximum current capacity in irrigated land for countries of the Basin as the upper limit on available land, more area can become available if greater long term water supplies can be secured and if institutions adjust to permit the extra water to be used by agriculture.

The baseline policy analysis is constrained to replicate historical irrigated land by country and crop. For the two alternative policies, those constraints are removed by allowing water trade-offs to occur, either within a single or among different irrigated areas. Either policy permits existing water to be reallocated to higher economic valued water uses where the economics would support such a reallocation.

A.6. Economics

Economic benefits are produced by water depletions at use nodes for irrigated agriculture and by the water flowing through turbines to generate energy at reservoir nodes. For agricultural uses, the willingness to pay is measured by the contribution of water to net farm income which equals crop price multiplied by yield minus cost of production plus any unpriced consumer surplus. Consumer surplus is an unpriced value, equal to the amount by which power buyers' economic welfare exceeds the actual price charged. It is measured as the area beneath the demand function and above actual price charged:

$$Con\_surp\_v(j,y,t,n,p) = 0.5 * [b0\_p(j) - Crop\_price\_v(j,y,t,n,p)] * sum(k, T\_production(j,k,y,t,n,p)) \quad (13)$$

For energy benefits, total revenue is measured as the price of electricity multiplied by the quantity produced. In the current implementation of the model, that electricity price is set at recent observed levels in the basin. Reduced prices from additional hydropower will raise consumer surplus, while increased prices will reduce consumer surplus. For regions of the basin that currently have little access to power, increases in consumer surplus are economically and politically important to achieve:

$$Energy\_ben\_v(res,y,t,n,p) = energy\_prod(res,y,t,n,p) * hydro\_price(res,t) \quad (14)$$

Agricultural benefits are measured as:

$$Ag\_ben\_v(use,y,t,n,p) = sum((j,k),(P\_p(j) * yield\_p(use,j,t) - cost\_p(use,j,t))) \quad (15)$$

Price of a particular crop is a negatively sloping demand function, which means that one price is set for each crop for all riparian countries, so any crop could be grown in the most favorable conditions. What this means is that:

$$Crop\_price\_v(j,y,t,n,p) = b0\_p(j) + b1\_p(j) * sum(k, T\_production\_v(j,k,y,t,n,p)) \quad (16)$$

The empirically estimated coefficients b0_p and b1_p are a linearized demand function based on estimated price elasticities.

To measure total crop production, the following equation is used:

$$T\_production\_v = sum(use, production\_v(use,j,k,y,t,n,p)) \quad (17)$$

A.7. Discounted net present value

Finally, the basin scale integrated model maximizes discounted net present value across all water uses, water environments, and time periods subject to hydrologic and institutional constraints:

$$DNPV\_v = sum\left((u,y,t) * \frac{Ag\_ben\_v(use,y,t,n,p)}{(1+r_u) ** t}\right) + sum\left((res,y,t)\frac{Energy\_ben\_v(res,y,t,n,p)}{(1+r_u) ** t}\right) \quad (18)$$

This says that the net present value of total water-based benefits for all nodes in the Amu Darya Basin sums income over countries and time-periods, which discounts future incomes more heavily when there is a higher discount rate. The current model implementation uses a 5% discount rate. The model allocates water among the basin's water uses, locations, and time periods to maximize *DNPV_v*, subject to the stated constraints.

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