How does the Rogun Dam affect water and energy scarcity in Central Asia?

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Abstract

The construction of the Rogun Dam in Tajikistan to increase upstream energy generation in the Amu Darya basin creates potential tradeoffs with existing downstream irrigation needs, due to the different timing of energy and irrigation water demands. This study applies a hydro-economic optimization model to quantify the impacts of dam operations on energy production and irrigation water availability for downstream uses. The analysis shows that cooperative basin-wide maximization of benefits leads to large increases in upstream hydropower production (93%), and only minor changes in the value of summer water availability to downstream irrigators (-1%). If irrigation production is prioritized in the basin as was the case during Soviet times, the construction of Rogun would increase irrigation benefits by a mere 2% while still substantially increasing hydropower benefits. If upstream stations, including Rogun, are managed unilaterally to maximize energy production benefits, however, hydropower benefits might more than double (116%) while irrigation benefits greatly decrease (-31%), thereby substantially reducing overall energy and irrigation benefits (-18%). This suggests that some combination of a basin-wide agreement over dam operations, a benefit-sharing mechanism, and a transparent inspection and safety certification system is needed prior to construction to ensure that risks are properly managed and that all affected parties can benefit from the project.

Keywords: Hydro-economic model, basin management, water allocation, hydropower, irrigation, Aral Sea Basin

Introduction

Achieving water, food and energy security in the context of increasing population and economic development is a key global challenge facing societies in many countries today. Complicating this challenge is the high degree of interconnection across the water, food and energy sectors, as evidenced by the high degree of correlation of food and energy prices, and the strong dependence of food production on water availability (Ringler et al., 2013). Indeed, irrigation is responsible for 70% of global freshwater withdrawals and is used to generate 40% of global food (Molden, 2007; Rosegrant et al., 2009), while hydropower contributes 16% of the global supply of electricity (Lucky, 2012). Despite these and other interlinkages (e.g., the use of energy as an input to agriculture), planning in the food and energy production sectors is typically uncoordinated. Moreover, management of these sectors involves various specialized institutions, with disparate government agencies providing regulation. Meeting national water, energy and food needs might also require imports of some or all of these resources from neighboring countries or faraway places, with often differing strategic interests.

Integrated management and planning of these sectors can be an important means to increase the benefits of resource use and thus improve livelihoods where water, food and energy resources are scarce. One tool to support such an integrated approach is the river basin hydro-economic model (HEM), which links water users across space and time (Rosegrant et al., 2000; Ringler et al., 2004; Harou et al., 2009; Wu et al., 2013). Hydro-economic and other, similar systems planning models allow analysis of a) the effects of current policies and tradeoffs across diverse competing uses for water resources, b) future changes in infrastructure or institutions governing water allocation; and c) vulnerabilities to future hydrological or other changes that affect water supply and demand.

This paper develops and applies an integrated approach to the second of these issues, namely assessment of a controversial infrastructure project located in the Aral Sea Basin, a transboundary river basin located in Central Asia (Eshchanov et al., 2011). The Rogun Dam is located on the Vakhsh tributary of the Amu Darya River in Tajikistan, and is principally a hydropower project. The project has a long history: construction was first initiated in 1976, but progress slowed and the project was eventually suspended due to the collapse of the Soviet Union. Since 1991, a series of disagreements first with Russia and then with other basin riparians have effectively blocked financing for the project. Recently, the World Bank conducted a four-year analysis of the feasibility of Rogun that assessed the technical, economic, environmental, and social aspects of the project (World Bank, 2014; Hashimova, 2014), and that may help further develop the plans for financing and construction of the project, should other riparians agree to it.

Even when designed with a specific purpose in mind (e.g., hydropower), dams such as Rogun can serve a variety of purposes and cause a wide range of positive and negative impacts. Water storage projects can provide water for irrigation or other downstream users at times of the year when water is scarce or during prolonged droughts, produce electricity when water is released through hydropower turbines, and allow smoothing of flows to mitigate floods or ensure minimum supply for maintaining ecosystem services. Conversely, dam operations can reduce downstream water availability during part of the year and disrupt existing and sensitive hydrological processes. A socially optimal regime of water releases from control infrastructures may not always preserve critical benefits to all riparian water users, and may require a balancing of efficiency with equity across multiple affected parties. In this sense, the Rogun dam proposal raises important questions that relate to its potential impacts on the water, food, and energy security of the major Amu Darya riparians.

Although hydropower generation does not entail consumptive water use, except insofar as storage increases evaporation and seepage losses from reservoirs, it may alter the seasonal pattern of water releases in the Aral Sea Basin in significant ways, with implications for downstream users (Wegerich, 2008; O'Hara, 2000). In the Amu Darya system, downstream irrigation, which is mainly located in Uzbekistan and Turkmenistan, requires sufficient delivery of water – and therefore releases from storage – in summer. In contrast, hydropower generation and releases are most beneficial in winter when energy demand is high. Upstream countries tend to argue for increasing energy production while also suggesting that storage provides downstream gains in dry years when water supplies are lacking (BIC, 2013). Downstream countries meanwhile contend that irrigation water availability during the critical summer season is reduced by operating rules that fill reservoirs during summer months in order to allow for greater release for energy generation in the winter, and that these releases cause flooding and infrastructure damage downstream (BIC, 2013; Spoor & Krutov, 2003). The seismic risks of construction of very high dams in this zone have been also emphasized (Eshchanov et al., 2011; BIC, 2013).

This study starts with a brief description of the study area and of the HEM used to analyze the effects of the Rogun Dam. We then present the results of the modeling analysis, prior to discussing them as well as other relevant issues – namely the seismic and political risks of construction of this dam. The paper concludes with additional remarks and policy implications.

A hydro-economic basin management model of the Aral Sea Basin

A brief description of the study area

The territory of the Amu Darya catchment (Fig. 1), which is part of the larger Aral Sea Basin, is characterized by a diversity of natural landscapes including mountains, valleys, deserts, lakes, and rivers (Bekchanov, 2014; p. 29). The Amu Darya is the largest river in Central Asia with a catchment area of 309,000 km^2 and an annual average flow of 73 km^3 (Bekchanov, 2014; p. 31). The river system flows 2,574 km from the headwaters of the Pyanj River on the Afghan-Tajik border to the Aral Sea (SANIIRI, 2004), and its catchment lies in four countries – Tajikistan, Uzbekistan, Turkmenistan and Afghanistan (McKinney, 2004).

The basin has a distinctly continental climate (UNEP, 2005) with precipitation occurring mainly during the winter in the form of snow, and during spring rains, outside of the annual growing season. Snow and glacier melt however provide the majority of river flows. As such, historical discharges were minimal in winter and peaked during the summer growing season. In addition, given the hot summers and the lack of substantial summer rainfall, net evapotranspiration during the growing season is high. As such, many parts of the basin, especially towards the downstream end of the system, require irrigation to sustain crop cultivation. Groundwater sources contribute about 3-4% of total irrigation water consumption.

Irrigated agriculture and rural settlement emerged over the centuries along the banks of the Amu Darya (Tolstov, 2005). The dominance of this rural agrarian lifestyle has largely been retained in the present, and over 60% of the population continues to derive their livelihoods from agricultural activities, primarily producing cotton, wheat, rice, fruit, and vegetables (Bekchanov et al., 2010). During the Soviet era, the USSR added to the importance of agriculture in the region by making large investments in upstream water control and in expansion of downstream irrigated agriculture; these investments were mostly geared towards expansion of cotton production (Micklin, 2007; Dukhovny & Schutter, 2011). Irrigation expansion led to the gradual desiccation of the Aral Sea and increasing levels and losses of water in tail-end depressions beyond irrigation sites, such as in

Sarykamysh. Today, agriculture continues to play a key role in the regional economy via its contribution to incomes and employment (Bekchanov & Bhaduri, 2013), which is nonetheless affected by increasing development of the river's hydropower potential (Weinthal, 2001; Wegerich et al., 2007). Since the dissolution of the Soviet rule in Central Asia, there have been reports of water insufficiency to meet the demands of downstream irrigators, suggesting that upstream developments may be affecting the availability of irrigation water (O'Hara, 2000; Micklin, 2007).

Building on these observations, this study develops a HEM for the purpose of analyzing the agricultural and hydropower production impacts of the Rogun Dam. If the dam was built to full scale, it would have an energy production capacity of 3,600 MW (EADB, 2008) and a height of 335 meters, which would make it the highest dam in the world (Schmidt et al., 2006; World Bank, 2014).

The hydro-economic model

A range of approaches (e.g., Input-Output, Computable General Equilibrium [CGE], and node-link based river basin simulation or optimization models) can be found in the literature analyzing the impacts of planned dams (Malik, 2007; Strzepek et al., 2008; Jeuland et al., 2013; Jeuland & Whittington, 2014; Robinson & Gueneau, 2014). This paper develops a node-link based optimization approach, since this approach is particularly useful for analyzing potential tradeoffs between water uses across economic sectors and for determining the socially optimal patterns of water releases from existing and new dams (Chatterjee et al., 1998; Harou et al., 2007). Such node-link based optimization models allow a detailed spatial representation of the hydrological regime and of water demand relationships of different economic sectors, such as irrigated agriculture, hydropower, and industries; environmental benefits; and domestic consumption (Rosegrant et al., 2000; Cai et al., 2003; Ringler et al., 2004). They also have important limitations. In particular, optimization models generally assume perfect foresight of future hydrology, and thus may overstate benefits relative to what is achievable in real-world operations. Even so, such HEMs do provide a starting point for comparisons of the potential efficiency of different water allocation alternatives and mechanisms (Booker & Young, 1994), and of the benefits of greater water cooperation and/or coordination (Whittington et al., 2005; Jeuland et al., 2014).

In this study, we developed a HEM that considers the distinct features of the Amu Darya Basin. Given the prevailing land and water allocation distortions that exist in this basin (Anderson, 2009) and preclude calibration of existing uses based on the equimarginal principle, we applied a normative programming approach to run and solve the model. As with many similar applications in the literature, the model operates on a monthly time step over the course of a year. The model was coded in GAMS and solved using the CONOPT 3 solver (Brooke et al., 2006). In what follows below, we provide additional details on the model set-up and analysis, specifically the basin schematic, objective function, model constraints, data sources for parameterization, and scenario analyses discussed in this paper.[1]

River basin schematic

The basic schematic of the model used for analyzing water allocation in the Amu Darya Basin considers inflows from 13 major tributaries, water diversions from 5 river nodes to 14 irrigated

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[1] Only the main components of the hydro-economic model are described in this section. For additional model details, the reader is referred to the more detailed description provided in Bekchanov (2014).

areas, and 3 reservoirs and hydropower production stations, including the Rogun Dam (Fig. 1). Although several other, smaller reservoirs exist or are in the planning stages, most of these are temporary off-river storage reservoirs that are filled by pumping and used mainly for the purpose of facilitating delivery of irrigation water. Since these smaller structures have little impact on monthly flows, they are not included in the model, which only contains the largest and most important reservoirs.

Since irrigation uses more than 90% of total water consumption in the Amu Darya basin and because the temporal pattern of irrigation water availability is potentially affected by upstream hydropower production developments, we considered these two main economic sectors in the model. Because of the high impact of irrigation expansion on environmental systems in this region, environmental flow benefits were also included. Finally, because the municipal and industrial sectors use less than 10% of total water consumption and are prioritized over other sectors in water allocation decisions, the model imposes fixed water consumption by these sectors.

<<Insert Fig. 1 here>>

Model objective function

The objective of the model is to optimize the sum of basin-wide benefits (π) from irrigation (IB_{dem}) at agricultural demand sites (dem), hydropower production (HP_{st}) at power production stations (st), and environmental benefits (EB)[2]:

$$\pi = w^{irr} \sum_{dem} IB_{dem} + w^{hp} \sum_{st} HP_{st} + EB. \tag{1}$$

In equation 1, the terms w^{irr} and w^{hp} are weights that can be varied to assess tradeoffs if either irrigation or hydropower is favored.

<u>Irrigation benefits</u>. Irrigation benefits (in million \$) are calculated as the difference between total crop production revenues and the costs of crop production, water delivery, return water use, and groundwater pumping:

$$\begin{aligned} IB_{dem} &= \sum_{cp} 10^{-6} \cdot \left(A_{dem,cp} \left(pr_{dem,cp} Y_{dem,cp} - pc_{dem,cp} \right) \right) \\ &- cc_{dem} \sum_{t} TWF_{dem,t} - ruc_{dem} \sum_{t} \sum_{cp} RU_{dem,cp,t} \qquad (2) \\ &- wpc_{dem} \textstyle\sum_{gw \in gwdlink} \sum_{t} \sum_{cp} WP_{gw,dem,cp,t}; \end{aligned}$$

where $A_{dem,cp}$ is the area of a particular crop (cp) in a certain demand site (dem) (in hectares); $pr_{dem,cp}$ is crop price (in \$/metric ton); $Y_{dem,cp}$ is crop yield (in metric ton/hectare); $pc_{dem,cp}$ is the cost of cultivation that does not include irrigation costs (in \$/hectare); cc_{dem} is the conveyance cost per unit of water delivered (in \$/m^3); $TWF_{dem,t}$ is the water delivered to the field in each

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[2] Endogenous variables are written using upper case letters while exogenous factors (model parameters) and identifiers (sets) are written with lower case letters in this section.

month (t) (in million m^3/month); ruc_{dem} is the pumping cost of diverting return flows for irrigation (in \$/m^3); $RU_{dem,cp,t}$ is the re-use of return flow (in million m^3/month); wpc_{dem} is groundwater pumping cost (in \$/m^3); and $WP_{gw,dem,cp,t}$ is the volume of pumped water from groundwater sources (gw) (in million m^3/month).

Crop yield levels are modeled using the FAO method that seeks to account for seasonal and overall water scarcity. Specifically, yield depends on maximum attainable yields ($my_{dem,cp}$) and the real yield rate that is unitless and varies between 0.1 and 1 ($RY_{dem,cp}$) and:

$$Y_{dem,cp} = my_{dem,cp} RY_{dem,cp}. \tag{3}$$

This real yield rate is a function of the fraction of deficits relative to the ideal crop water requirement (Ringler et al., 2004; Cai et al., 2006).[3] Specifically, $RY_{dem,cp}$ is related to the maximum crop growth stage deficit ($MDFT_{dem,cp}$) as follows:

$$RY_{dem,cp} \leq 1 - MDFT_{dem,cp}. \tag{4}$$

The maximum stage deficit is obtained from the set of monthly stage deficits ($DFT_{dem,cp,pd}$), which are estimated following Doorenbos and Kassam (1979) (see also Ringler et al., 2004):

$$DFT_{dem,cp,t} = ky_{cp,t}\left(1 - \frac{ETST_{dem,cp,t}}{10^{-5}\cdot A_{dem,cp}\cdot etm_{dem,cp,t}}\right); \tag{5}$$

$$MDFT_{dem,cp} = \max_t\left\{DFT_{dem,cp,t}\right\}; \tag{6}$$

where $ky_{cp,t}$ is the crop coefficient, $ETST_{dem,cp,t}$ is actual crop evapotranspiration by month (in million m^3), $etm_{dem,cp,t}$ is crop reference evapotranspiration (in mm).

The real yield rate ($RY_{dem,cp}$) cannot be larger than the seasonal relative crop yield ($SRY_{dem,cp}$):

$$RY_{dem,cp} \leq 1 - SRY_{dem,cp}. \tag{7}$$

Seasonal relative crop yield ($SRY_{dem,cp}$) is defined based on the FAO formula (Doorenbos & Kassam, 1979; Ringler et al., 2004) that includes the seasonal crop coefficient (kyc_{cp}):

$$SRY_{dem,cp} = 1 - kyc_{cp}\left(1 - \frac{\sum_t ETST_{dem,cp,t})}{10^{-5}\cdot \sum_t A_{dem,cp} etm_{dem,cp,t}}\right). \tag{8}$$

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[3] It is important to note that this formulation of the economic benefits from water allocation to irrigation does not represent the diminishing returns to increased water use that is most relevant for decision-making changes in water allocation to farmers (Young & Loomis, 2014). A more fully consistent approach would better account for nonlinearities in the yield curve as a function of water input, as well as substitution of different inputs of labor, land and capital.

Hydropower benefits. The second component of benefits, from hydropower generation (in million \$), is calculated using equation 9:

$$HP_{st} = 10^{-3} \cdot \sum_t epr_t EP_{st,t}; \tag{9}$$

where epr_t is the price per unit of electricity output (in \$/kW-hr in month *t*) and $EP_{st,t}$ is the amount of electricity generated (in MW-hr in month *t*).

Electricity production for the stations ($EP_{st,t}$) located at the outlet of reservoirs ($(rev, st) \in RPLINK$) is modeled as a multiplicative function of production efficiency, water elevation, and release through the turbines:

$$\begin{gathered} EP_{st,t} = \rho \cdot ste_{st}\big(0.5\, H_{rev,t} + 0.5\, H_{rev,t-1} - htail_{rev})\big) \\ \sum_{rev \in RPLINK}\big((\sum_{rn \in RNLINK} RSN_{rev,rn,t} + \sum_{rev\_lo \in DDLINK} RRS_{rev,rev\_lo,t}\big)\ ; \end{gathered} \tag{10}$$

where $RSN_{rev,rn,t}$ is river flow (in million m^3/month) from reservoir (rev) to node (rn) if a link between these exists (in $RNLINK$); $RRS_{rev,rev\_lo,t}$ is flow (in million m^3/month) from an upstream reservoir to the next downstream reservoir (rev_lo) if a link between these exists ($DDLINK$); the head ($0.5\, H_{rev,t} + 0.5\, H_{rev,t-1}$) is calculated as the average water elevation in the reservoir at the end of the previous and current period (in m); $htail_{rev}$ is the tail-water level of the reservoir (in m); ste_{st} is the unitless production efficiency of the reservoir; and ρ is a constant for conversion to power units.

Similarly, hydroelectricity generation at run-of-river power stations is estimated as:

$$EP_{st,t} = \rho \cdot \big(\sum_{rn \in NPLINK} \sum_{rn\_lo \in RVLINK} FL_{rn,rn\_lo,t}\big) ry_{rev}\ ste_{st}; \tag{11}$$

where $FL_{rn,rn\_lo,t}$ is river flow (in million m^3/month) from an upstream node (rn) to the next downstream node (rn_lo) in each month (t) if a link between these nodes ($RVLINK$) exists; and ry_{rev} is the head (in MW-hr per million m^3) that indicates the amount of electricity generation per unit of river flow.

Environmental benefits. The third component of benefits in the objective function corresponds to the economic value of inflows into the Aral Sea and deltaic zones (EB). Following Bekchanov (2014), these benefits are considered to be a linear function of the total monthly environmental flows to the downstream end of the system (EF_t):

$$EB = b0\ + b1 \sum_{pd} EF_t; \tag{12}$$

where $b0$ and $b1$ are parameters of the environmental benefit function and EF_t is the monthly environmental flow (in million m^3) from the Amu Darya (the node link "Amu5 → THE ARAL SEA") into the Aral Sea[4]. Flows into tail-end depressions beyond the irrigation sites in the Basin are assumed to provide no environmental value; such flows are low in quality, and do not produce significant environmental amenities.

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[4] For a detailed description of the environmental benefit function and its estimated parameters, see Bekchanov (2014: p. 135-141).

Model constraints

Flow continuity constraints. The model is solved subject to a range of water balance constraints imposed at each river node (equation 13) and reservoir (equation 14):

$$\begin{aligned}&\sum_{rn\_up \in RVLINK} FL_{rn\_up,rn,t} + src_{rn,t} + \sum_{rev \in RNLINK} RSN_{rev,rn,t}\\ &+ \sum_{dem \in DNLINK} RFR_{dem,rn,t} + \sum_{gw \in GWRLINK} DSCH_{gw,rn,t}\\ &= \sum_{rn\_lo \in RVLINK} FL_{rn,rn\_lo,t} + \sum_{rev \in NRLINK} NRS_{rn,rev,t}\\ &+ \sum_{dem \in NDLINK} (RW_{rn,dem,t} + idw_{rn,dem,t})\end{aligned} \tag{13}$$

$$\begin{aligned}&V_{rev,t-1} + \sum_{rn \in NRLINK} NRS_{rn,rev,t} + \sum_{rev\_up \in DDLINK} RRS_{rev\_up,rev,t}\\ &= V_{rev,t} + \sum_{rn \in RNLINK} RSN_{rev,rn,t} + \sum_{rev\_lo \in DDLINK} RRS_{rev,rev\_lo,t}\\ &+10^{-3}\, evapr_{rev,t}\, (0.5\, S_{rev,t-1} + 0.5\, S_{rev,t})\end{aligned} \tag{14}$$

In equation 13, for each month *t*, $FL_{rn\_up,rn,t}$ is the river flow (in million m^3) to node rn from the upper node (rn_up); $src_{rn,t}$ is the inflow from river tributaries (in million m^3); $RSN_{rn,rev,t}$ is river flow from an upstream reservoir *rev* to node *rn* (in million m^3); $RFR_{dem,rn,t}$ is return flow from upstream irrigation demand site *dem* to the river node *rn* (in million m^3); $DSCH_{gw,rn,t}$ is water seepage to the river from groundwater source gw if a link exists ($GWRLINK$) between it and river node rn (in million m^3). Conversely, $FL_{rn,rn\_lo,t}$ is the river flow (in m^3) from node rn to the next lower node (rn_lo); $NRS_{rn,rev,t}$ indicates river flow from a node *rn* (in million m^3) to downstream reservoir *rev*; and $RW_{rn,dem,t}$ and $idw_{rn,dem}$ are water withdrawals from node rn to irrigation and industrial and municipal water users, respectively, if a link exists between the node and the water user site ($NDLINK$) (in million m^3).

All terms are defined similarly in equation 14. In addition, $V_{rev,t}$ is reservoir storage volume at the end of month *t*, $RRS_{rev\_up,rev,t}$ is flow to a downstream reservoir (rev) from an upper reservoir (rev_up); $evapr_{rev,t}$ is the rate of evaporation from the surface of the reservoir (in mm); and $S_{rev,t}$ is the surface area of the reservoir (in million m^2).

Reservoir morphological parameters. The surface area of the reservoir at time t is estimated using a cubic function:

$$S_{rev,t} = c0 + c1\, V_{rev,t} + c2\, V_{rev,t}^{2} + c3\, V_{rev,t}^{3}; \tag{15}$$

where $c0$, $c1$, $c2$, and $c3$ are the parameters of the function that correspond to the best-fitting cubic function for this relationship. Similarly, the water level in the reservoir ($H_{rev,t}$) is estimated based on the reservoir storage volume:

$$H_{rev,t} - htail_{rev} = d0 + d1\, V_{rev,t} + d2\, V_{rev,t}^{2}; \tag{16}$$

where $d0$, $d1$, and $d2$ are the parameters of the function that correspond to the best-fitting quadratic function for this relationship.

Other constraints. Other model constraints limit the reservoir storage, hydropower production according to installed generation capacity, and irrigated area according to available irrigable land. To prevent unjustified use of stored water, e.g., to avoid "stealing water from the future", initial levels of all reservoirs are forced to equal the levels at the end of the planning period. Finally, there are constraints on the total volume of return flows that can be reused, since irrigators in the basin resist use of such water with high salinity beyond a certain point.

Database of the model

In order to parameterize the model over such a large study area spanning several countries, a consistent database had to be assembled using multiple sources.[5] Monthly water flows to supply nodes; irrigation water withdrawals, cropping patterns and yields; and industrial and municipal demands were obtained from the CAREWIB database (SIC-ICWC, 2011).

Data on potential crop evapotranspiration coefficients and effective rainfall were sourced from IFPRI's IMPACT model (2013). Crop production costs and prices for agricultural areas in the model were specified using data from Uzbekistan, obtained from a range of reports from local water management organizations (SIC-ICWC 2008), as well as surveys (ZEF/UNESCO Uzbekistan Project). All prices were adjusted to 2006 levels (the year corresponding to most of the data used in the model). Conveyance costs across the sites come from MAWR (2007). To avoid systematic bias due to policy distortions that affect input and output prices differently across countries, the data from the closest regions in Uzbekistan were applied to agricultural areas in the other countries.[6] The price differences across different regions of Uzbekistan stem from quality differentiation and variable access to markets, rather than differences in policies. For example, farmers in Surkhandarya province are paid higher prices per unit of cotton output because the quality of cotton produced in this region is higher than in other regions.

Electricity production capacity, electricity prices, reservoir storage capacity and releases are based on Cai (1999) and the BEAM and ASBOM model databases (EC IFAS, 2013; SIC-ICWC 2003).

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[5] For access to additional database details or the data used in this article, please contact the corresponding author.

[6] For instance, farmers in Kazakhstan obtain greater benefits per unit of water than farmers in Uzbekistan despite lower yields, largely because of liberalized prices.

The reservoir elevation and surface area parameters come from EC IFAS (2013) and SIC-ICWC (2003).

Analytical scenarios

In the next section, we examine the impacts of the Rogun Dam on water allocation, hydropower and irrigation benefits through the comparison of three distinct optimization scenarios. In scenario 1 (COOP), total benefits from the system are maximized; this corresponds to the efficient basin-wide allocation of water with Rogun (COOP/+) and without it (COOP/-).[7] Scenario 2 (DWSMX) then re-optimizes the system from the perspective of irrigation interests in the basin, i.e., downstream irrigation benefits are prioritized through weighting factors w^{irr}. In scenario 3 (UPSMX), the perspective is switched to one that considers primarily hydropower production benefits, i.e., w^{hp} is instead given this large weight in the objective function. The changes from adding Rogun are then measured in relation to the cooperative case without Rogun (scenario COOP/-). Since the current regime may not reflect full cooperation, we also report the changes relative to the other "baselines" that do not include Rogun (specifically, DWSMX/- and UPSMX/-).

To test the sensitivity of the cooperative model results to changes in flow, we run the model first using the hydrology from 1999, which was a normal year over the 1980-2008 period. We then re-run the model with reduced water supply scenarios that assume a uniform reduction in inflows throughout the basin and in all months, of 10% and 20% relative to these normal levels. These reductions are designed to assess the sensitivity of the results to anticipated drying in this region due to future climate change (Chub, 2007).

Because of the static nature of the model, the model does not account for the temporal dynamics of net benefits during the construction and filling period for the dam. As such the analysis should not be considered a benefit-cost analysis of Rogun, which would require accounting for transient effects and relaxing of the assumption of perfect foresight. In addition, the results in this paper only show the sensitivity of outcomes to reduced flows, and do not account for the uncertainty associated with stochastic flow variation or deep uncertainty about future climate change (Groves & Lempert, 2007).

Results

In this section, we begin by comparing the results of Scenario 1 with historical data on water allocation and production to put the optimized results into context. We then discuss the effects of Rogun Dam under cooperation (Scenario 1) and non-cooperation scenarios (Scenarios 2 and 3).

Comparison of observed and optimal values of the variables considered in the model

To better put into context the results of optimizing water allocation from the Amu Darya system, we first compare historical and optimal (COOP/-) water allocations, irrigated land areas, and crop yields for two key crops – cotton and wheat (Table 1). Under basin-wide optimization, the area of irrigated land would be reduced in Khorezm (-17.7%), Karakalpakstan (-14.6%), and Ahal (-7.0 %), and increased in Samarkand (161%), Surkhandarya (104%), and Kashkadarya (65%). As a

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[7] To put the optimal results into context, we also compare the results of Scenario 1 (without Rogun) with historical data on water allocation and agricultural production.

result of increased water application, substantial increases in cotton yields could be obtained in Lebap (69%), Navoi (42%), and Bukhara (31%), while yields in Karakalpakstan would be reduced (39%). With regards to wheat, substantial increases in yields would occur in Bukhara (148%), Kashkadarya (111%), and Karakalpakstan (82%) provinces.

<<Insert Table 1 here>>

Comparison of optimization scenarios with and without Rogun Dam

Following construction of the dam, the optimal solution does not point to large changes in total cropped area across irrigation sites (Table 2). Irrigation water withdrawals, however, decline considerably in two sites: Surkhandarya (by 1.1 km^3) and Lebap (by 0.2 km^3). Furthermore, the reduction of withdrawals in Surkhandarya increases the re-use of return flows, which in turn decreases discharges to the tail-end depressions located beyond the irrigated sites by 309 million m^3.[8]

When all riparians cooperate for attaining basin-wide optimal gains, the impact of the dam on irrigation benefits is also limited and the dam does not change irrigation benefits for the majority of irrigation sites. In Surkhandarya, where water withdrawals decrease most substantially, irrigation benefits however decline by about 10%, or US$12 million/yr.

<<Insert Table 2 here>>

The pattern of releases from the existing Nurek reservoir (the largest hydropower dam in the basin at this time, which is located downstream of Rogun; see Fig. 1) provide an interesting perspective on the efficient water allocation solution in this basin. The model results indicate that higher demand for irrigation water during the summer growing season is partly met by releasing greater amounts of water from Nurek from July to September (Fig. 2). Releases are also higher in February, when energy demand is greater, and prices are higher. The addition of Rogun under normal flow conditions changes the pattern of these releases somewhat; the releases decrease slightly at the beginning of the summer season in July and August, and increase at the beginning of the winter season (December) in order to enhance the benefits from hydropower production. When water availability declines, however, the opposite pattern occurs: downstream releases increase slightly in summer months with the addition of Rogun, and releases in early winter decline slightly relative to the case without the dam.

<<Insert Fig. 2 here>>

Water releases from Nurek and Rogun and downstream irrigation water uses could be jointly managed to avoid harming downstream irrigation benefits if all riparian countries were to cooperate (Fig. 3). Under normal water supply, overall irrigation benefits in the Amu Darya basin under this cooperative case reaches US$ 1.76 billion without the Rogun Dam and barely declines by US$0.02 billion (1.1%) to US$ 1.74 billion when the dam is constructed. Under reduced water supply (by 20%) overall irrigation benefits decline; the addition of Rogun under these conditions

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[8] Irrigators prefer to not use return flows due to their low water quality, and re-used water is not fully substitutable with freshwater. Constraints on use of return flows seek to prevent unrealistic levels of reuse water substitution. In future studies, more advanced models that consider soil and water salinity and leaching relationships may better incorporate farmer preferences for water source types, and better enable consideration of the water quality issues associated with increased re-use of drainage water.

would lead to a very small increase in irrigation benefits by US$0.03 billion (2.2%). Thus, optimal management of the dam leads to only minor impacts on downstream irrigation across different levels of water availability. Since most of the river flow in the system can already be controlled using current dams (Dukhovny & Schutter, 2011; p. 134), the benefits of the newly constructed dams for enhancing irrigation water availability are inconsequential. Under decreased water supply scenarios, irrigation benefits decline similarly regardless of whether Rogun is added to the system, due to the limited availability of water during the summer months.

<<Insert Fig. 3 here>>

While irrigation impacts are minor if all countries cooperate, Rogun dam may provide substantial gains in terms of energy production (Fig. 4). In an average hydrological year, power production benefits would nearly double from US$ 174 million to US$ 336 million. With a reduction in inflows by 20% the magnitude of additional benefits would decrease to US$ 108 million, which would still represent an 80% increase over the baseline configuration without Rogun. With modest transfers of these gains to downstream irrigators, irrigation losses (e.g., in Surkhandarya) could be compensated, making all parties better off.

<<Insert Fig. 4 here>>

Comparison of cooperation and non-cooperation scenarios with and without the Rogun Dam

Although full cooperation to achieve basinwide gains can provide substantial upstream hydropower gains (+93%) with very minor impacts on irrigation production (-1%), past experience in the basin suggests that unilateral maximization of either energy production or irrigation benefits could be possible up and downstream water management strategies. If upstream storage dams were regulated to maximize irrigation benefits (as occurred during the water regime in Soviet times), the addition of Rogun would increase total irrigation benefits by only 2% (DWSMX/+, Table 3). Due to Nurek's greater influence on flow regulation, Rogun does not play a significant role in helping to enhance summer flows for use in downstream irrigation. However, hydropower production benefits would increase by 63% relative to the baseline (COOP/-). In addition, holding infrastructure constant (e.g., comparing DWSMX/- with COOP/-; and DWSMX/+ with COOP/+), it can be noted from Table 3 that irrigation benefits under this DWSMX regime are only about 1-2% (US$15-42 million) higher than in the cooperative situation, whereas hydropower benefits decline by 13-16% (US$22-53 million).

Given recent changes in hydropolitics, a perhaps more likely scenario in the basin is that upstream hydropower production would be unilaterally optimized. The modeling results indicate that this hydropower-focused regime generates greater power benefits (+116%, or US$202 million) relative to COOP/-. Yet this increase comes at heavy costs to downstream irrigation benefits, which decline by 31% (or US$553 million). Again holding infrastructure constant (e.g., comparing UPSMX/- with COOP/-; and UPSMX/+ with COOP/+), we observe that irrigation benefits under the UPSMX regime are 11-31% (US$201-538 million) lower than in the cooperative situation, whereas hydropower benefits increase by 12-17% (US$30-40 million). Furthermore, this tradeoff worsens when Rogun is included (irrigation declines by US$538 million even as hydropower profits increase by only US$40 million).

<<Insert Table 3 here>>

Discussion

The Rogun Dam has long been controversial, in part because of concerns over unequal impacts on upstream and downstream riparians of the Amu Darya Basin (Wegerich, 2008; Eshchanov et al., 2011). The project may generate substantial energy gains in Tajikistan, the upstream riparian. Meanwhile, downstream water users, in Uzbekistan and Turkmenistan, expect that it would significantly reduce summer water availability and adversely affect irrigated agriculture. The river basin modeling conducted in this paper suggests that cooperative optimal basin-wide management would significantly increase hydropower production (by 93%) and also result in relatively minor adverse impacts downstream in the basin (-1%). The effects of the dam on downstream benefits however depend on the pattern of upstream reservoir water releases, and large losses (-31%) in the agricultural sector would occur if upstream hydropower production benefits were unilaterally maximized. In addition, unilateral operations would only marginally improve energy production benefits, such that overall system benefits would be reduced by 18%.

Distributional concerns are only one part of the dispute over Rogun. A variety of other issues – related to transient effects on water security, alternative energy options, earthquake and flood risks, and political power asymmetries – have received attention in the literature. Based on their prior experience with the Tokhtogul Dam, specialists from downstream countries expect that operation of the Rogun dam would be unilateral and purely for the purpose of hydropower production, and might also be used to serve various political objectives of the upstream riparians (BIC, 2013). A somewhat different dispute narrative posits that Rogun was part of a larger effort by Soviet specialists to increase regional discord and prevent regional cooperation, for the benefit of enhancing Moscow's influence in Central Asia (O'Hara 2000). Lange (2001) offers a contrasting view, arguing that upstream dams were planned and constructed at locations where they were more technically and economically relevant. As shown in Table 4, the basin has seen considerable development since the 1950s. Specifically, during the Soviet era, upstream dams were largely built to enhance summer water availability for downstream irrigation and to prevent flooding (Table 3, compare rows 1 and 2). In fact, the greater interest in hydropower development and shifting of dam operations in the greater Aral Sea Basin is relatively new since the fall of the Soviet Union (reflected in a shift in release patterns as shown in Table 4, row 3) (O'Hara 2000; Müller, 2006; Dukhovny & Schutter, 2011).

<<Insert Table 4 here>>

Somewhat related to such strategic and political considerations, downstream interests are worried about negative impacts on water security during the period immediately following construction of the dam. Depending on the filling rules implemented for the new reservoir behind Rogun, water flows to downstream users could decline significantly. Contributing to this concern is the prior regional experience in the late-1970s through mid-1980s, when frequent water shortages coincided with the addition of the Tokhtogul reservoir (Syr Darya Basin), and the filling of the Nurek reservoir (Dukhovny & Schutter, 2011). Future studies should assess the nature and magnitude of such transient filling impacts, using dynamic hydro-economic optimization or simulation models.

The Rogun Dam would add significant power generation capacity, and may thus significantly enhance energy security among the power-constrained economies of Central Asia (ADRC, 2006). This energy security calculation, however, largely depends on the relative generation and transmission costs of alternative supplies to end users, and on the distribution of the benefits of power generation. For example, Eshchanov et al. (2011) argue that upstream provinces have high capacity for adopting alternative energy technologies, and that these would carry lower safety and financial risks than a massive new multi-billion dollar dam. Furthermore, if the increased energy output is primarily used for export to foreign countries like India, Iran, Afghanistan, and Pakistan as previously reported (ADRC, 2006; Rizk & Utemuratov, 2012; Eshchanov et al., 2011), high transmission costs and additional investment needs may reduce net benefits. On the other hand, increased interconnection and mutually beneficial power trade deals within Central Asia, if economically attractive, may enhance the distributional outcomes of the Rogun project.

There are also important concerns about earthquakes occurring near the Rogun Dam location, which increases the risks of dam failure and catastrophic downstream flooding (BIC, 2013). The possibility of dam failure cannot be easily included in an annual optimization model of the type used in this paper, and so we instead offer a qualitative assessment based on information available in the literature. Global maps of earthquake intensity risk indicate that the location of the Rogun Dam is an area with extremely high seismicity (ISDR, 2008), and this risk has been confirmed by geological investigations during the design phase for Rogun (Schmidt et al., 2006; Gill et al., 2014). Frequent earthquakes reaching 6 to 7 on the Richter scale occur in the neighboring region; such events have provoked landslides, ruptures of the land surface and consequent destruction of several villages accompanied by loss of life (ADRC, 2006; Schmidt et al., 2006; Teshebaeva et al., 2014). If such an event were to compromise the integrity of the dam, it could lead to major flooding and destruction in communities located downstream. Prior to construction of the new dam, a detailed assessment of such risks is therefore essential, and should include recommendation and joint agreement by all affected parties on the measures required for mitigating risks and planning for emergency evacuation of populations from at-risk areas. In addition, the costs of these risk mitigation measures and of the risks of destruction should be incorporated into any economic cost-benefit analysis of the dam prior to deciding to move forward with construction.

The seasonal water tradeoffs between irrigation and hydropower production revealed in this analysis also relate to current challenges and conflicts over downstream water allocation in the study region. In this respect, it should be noted that preservation of ecosystems in the basin depends on improving the efficiency of water use in irrigation systems. At present large amounts of water are lost in depressions at the ends of irrigated areas; such water could possibly be transferred for recharge of previously vibrant environmental assets and ecosystems (particularly the Aral Sea) (Micklin 2007). Similarly, irrigation efficiency improvements at the farm- and canal-level could reduce return flows and water losses (Cai et al. 2003; Horst et al. 2005; Bekchanov et al. 2010) and thus could free up freshwater resources for restoring downstream ecosystems (Bekchanov et al. *in press*). However, irrigation improvements depend to a large extent on effective water institutions. For instance, if downstream producers invest in efficiency improvements but fail to obtain adequate water in time for their crops because of poor management of water releases, they will bear high socio-economic and financial risks. Thus, basin-wide coordination of the water releases and improved water management institutions are essential for creating incentives for improved water productivity (Bekchanov et al. 2015).

Summing up, on one hand, the model results presented in this paper support the idea that if the above issues can be resolved and strong cooperation among the riparian countries can be established the modest negative distributional impacts of the Rogun Dam on irrigators could be effectively managed. Such management would likely entail slight modifications of the release patterns from Nurek, the hydropower facility located immediately downstream of Rogun. A likely win-win option would involve optimizing Rogun for hydropower production in the winter season, and operating Nurek to then ensure sufficient releases of summer water to meet downstream water demands (Table 4, row 4). On the other hand, the most likely uncooperative solution that would include both Rogun and Nurek operated to maximize hydropower production in winter, would at best improve energy production benefits only by a small amount (US$40 million/yr) relative to the cooperative regime with Rogun. Yet this regime, as shown by the modeling results (Table 3), would have very substantial negative effects on downstream interests (harming them by US$538 million/yr) relative to the cooperative solution (Table 4, row 6).

Conclusions

As discussed above, when riparian countries cooperate there is a possibility for a win-win regime of water releases from a system of upstream reservoirs that include the Rogun Dam. Model results indicate that under this cooperation scenario optimal operation of reservoirs in the Amu Darya Basin only slightly reduces downstream water availability in a normal hydrological year, and negligibly increases it in dry years. Under a water regime that prioritizes irrigation, such benefits only slightly increase following construction of Rogun. In fact, the capacity of current reservoirs in this basin is already sufficient to regulate and balance seasonal and annual variability, such that construction of additional dams does not appear beneficial for downstream irrigators. In contrast, electricity production and benefits would increase substantially with the construction of Rogun. This increased energy production could improve regional energy security, particularly if a beneficial power trade agreement can be established between the basin riparians. Unfortunately, relative to a cooperation regime, there exists a high potential for significant harm to downstream users from unilateral maximization of hydropower production benefits (by 11 and 31% with and without Rogun, respectively). Seen from this perspective, the concern over Rogun among downstream interests in the basin is understandable, given that a) it is currently unclear whether they stand to benefit from the project; b) the dam may precipitate a shift towards a more hydropower-centered regime in the basin; and c) the dam carries potential political, safety, and transient risks. As such, engagement of the affected riparians in cooperative negotiations to build trust and reach mutual agreement over the operation and risk management of the Rogun Dam would seem advisable prior to restarting this project.

Despite the advantages of using hydro-economic optimization for considering the effects of this new project on the dynamics of water allocations throughout the Amu Darya Basin, the model has important shortcomings that should be addressed in future studies. Dynamic stochastic optimization and simulation approaches would provide a more complete and thorough understanding of the transient effects of dam construction, as well as uncertainties related to the economic and hydrological parameters that affect outcomes (e.g., climate change or development uncertainties). Such approaches could also partially account for the economic risks of dam failure, although this issue also mandates analysis from social and environmental perspectives. Though the dataset used in this study is recent and more consistent than that of many previous studies, data limitations – particularly with respect to variation across space and time – may somewhat bias the results. Finally, although the analysis explicitly tracks water allocations to different downstream users, the model does not address the general equilibrium effects of power production and changes in agriculture-sector output. A CGE analysis might additionally reveal the impacts of infrastructural changes on employment and income distribution patterns and allow for an improved analysis of water use, energy production and use, and food production interlinkages.

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LIST OF TABLES

Table 1 Comparison of observed and optimal land and water uses and crop yields by irrigation sites

	Cropland areas (1000 ha)			**Total water use (km^3)**			**Cotton yield (ton per ha)**			**Wheat yield (ton per ha)**		
	OBS	**OPT**	**CHN**	**OBS**	**OPT**	**CHN**	**OBS**	**OPT**	**CHN**	**OBS**	**OPT**	**CHN**
GBAO	28	28	0.9	0.4	0.3	-17	0.0	0.0		2.0	2.4	24
Khatlon	308	308	-0.1	5.6	2.8	-50	2.9	3.2	9	6.9	11.3	63
RRT	79	81	2.6	0.7	1.0	51	2.8	3.1	10	2.7	4.0	50
Surkhandarya	398	380	-4.4	3.8	7.7	104	2.0	2.3	13	2.0	2.4	20
Mary	442	442	0.0	6.5	7.6	16	2.8	3.1	11	4.2	6.8	61
Ahal	405	377	-7.0	4.9	5.4	10	2.0	2.4	21	1.2	0.6	-49
Lebap	262	261	-0.1	4.6	5.3	15	1.6	2.7	69	1.1	0.8	-29
Kashkadarya	549	550	0.1	4.9	8.1	65	2.8	3.3	20	4.9	10.2	111
Samarkand	514	515	0.1	3.3	8.7	161	2.2	2.5	12	11.9	13.6	14
Navoi	146	139	-5.2	2.0	2.8	42	1.7	2.4	42	1.0	0.6	-41
Bukhara	238	231	-3.1	4.0	5.0	24	1.6	2.1	31	1.3	3.2	148
Khorezm	217	178	-17.7	4.6	4.7	3	2.3	2.4	5	1.4	1.4	1
Karakalpakstan	364	311	-14.6	7.7	7.3	-6	2.0	1.2	-39	2.0	3.6	82
Dashauz	371	371	0.1	6.6	9.5	44	2.4	2.8	16	2.2	2.6	19
Total	**4321**	**4173**	**-3.4**	**60**	**76**	**28**						

Notes: “OBS”-Observed, “OPT”-Optimal, “CHN” – Change (in %)

Table 2 Comparison of optimal land and water uses, and irrigation benefits by irrigation sites with and without Rogun

	Cropland use (1000 ha)			Water use (million m^3)			Irrigation benefits (million USD)		
	OPT-	OPT+	CHN	OPT-	OPT+	CHN	OPT-	OPT+	CHN
GBAO	28	28	0	299	299	0	35	35	0
Khatlon	308	308	0	2809	2809	0	177	177	0
RRT	81	81	0	1020	1020	0	59	59	0
Surkhandarya	380	380	0	7678	6578	-1100	128	116	-12
Mary	442	442	0	7559	7559	0	218	218	0
Ahal	377	377	0	5412	5412	0	67	67	0
Lebap	262	262	0	5326	5154	-172	135	133	-2
Kashkadarya	550	550	0	8131	8131	0	377	377	0
Samarkand	515	515	0	8660	8660	0	198	198	0
Navoi	147	143	-4	2841	2841	0	43	43	0
Bukhara	231	239	8	4953	4953	0	81	81	0
Khorezm	178	209	31	4684	4625	-59	51	50	-1
Karakalpakstan	311	311	0	7265	7265	0	15	15	0
Dashauz	371	371	0.0	9466	9466	0	175	175	0
Total	4181	4216	34.8	76104	74772	-1331.7	1759	1744	-15.3

Notes: “OPT –“ – Optimal without Rogun, “OPT+” – Optimal with Rogun, “CHN” – Change

Table 3 Irrigation versus hydropower production trade-offs in average water year under both cooperation and non-cooperation scenarios

Trade-off scenarios	Benefits (US$ million)			Change relative to COOP/- (%)		
	Irrigation	Hydropower	Total	Irrigation	Hydropower	Total
COOP/-	1759	174	1933	0	0	0
COOP/+	1744	336	2080	-1	93	8
DWSMX/-	1774	151	1926	1	-13	0
DWSMX/+	1787	283	2070	2	63	7
UPSMX/-	1559	204	1762	-11	17	-9
UPSMX/+	1206	376	1582	-31	116	-18

Notes: "-" – without Rogun; "+" – with Rogun; "COOP" – full cooperation; "UPSMX" – unilateral maximization of upstream hydropower production benefits; "DWSMX" – unilateral maximization of irrigation benefits

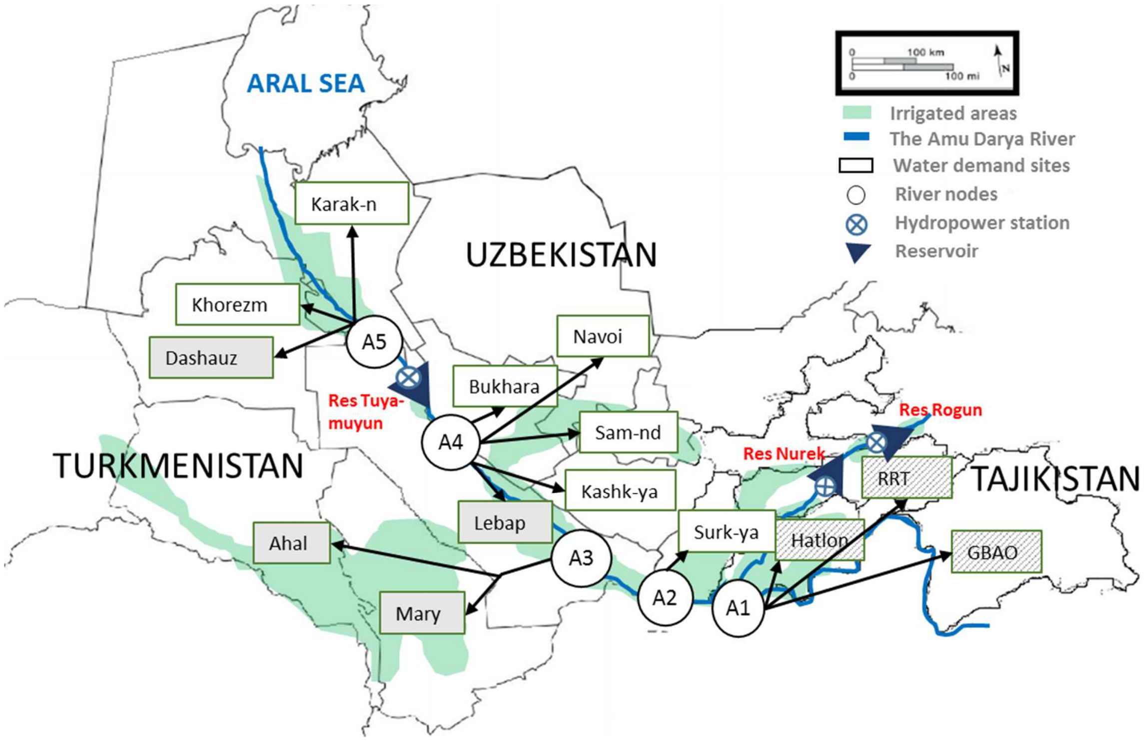
Table 4 Qualitative assessment of changes in irrigation and energy benefits under different reservoir water release regimes

#	Period	Corresponding modeling scenario	Period for dominant water release		Impact on irrigation and energy production benefits		Likelihood
			by the Rogun reservoir	by the Nurek reservoir	Irrigation benefit	Energy benefit	
1	Baseline*: Before 1950s	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2	Before 1990s	COOP/- or DWSMX/-	n.a.	Summer	+++++	++	n.a.
3	At present	UPSMX/-	n.a.	Winter	++++	+++	n.a.
4	Future option A	COOP/+	Winter	Summer	+++++	+++++	Likely**
5	Future option B	DWSMX/+	Summer	Summer	+++++	++++	Unlikely
6	Future option C	UPSMX/+	Summer or winter	Winter	++	+++++	Likely***

Notes: n.a. – not applicable, 0- no change or no considerable change relative to baseline, "+++++" – substantial increase relative to baseline, "+++" – moderate increase relative to baseline, "+" slight increase relative to baseline. *Baseline benefits (before 1950s) are assumed as 50% of benefits under cooperation scenario (COOP/-); **Win-win scenario that requires mutual trust and cooperation; ***Depends on geopolitical interests

LIST OF FIGURES

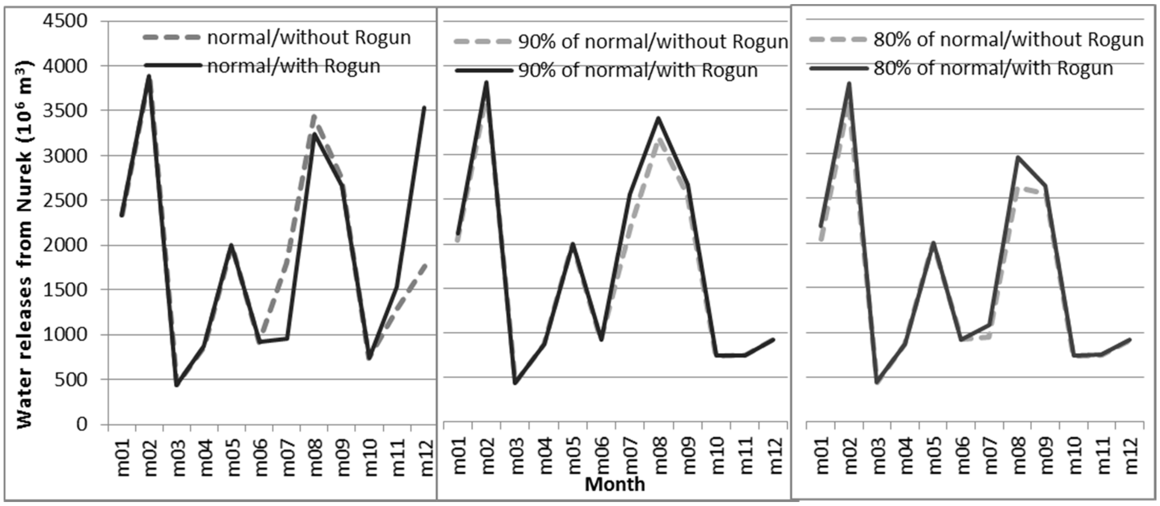
Figure 1 Amu Darya River basin scheme



Source: Authors' presentation

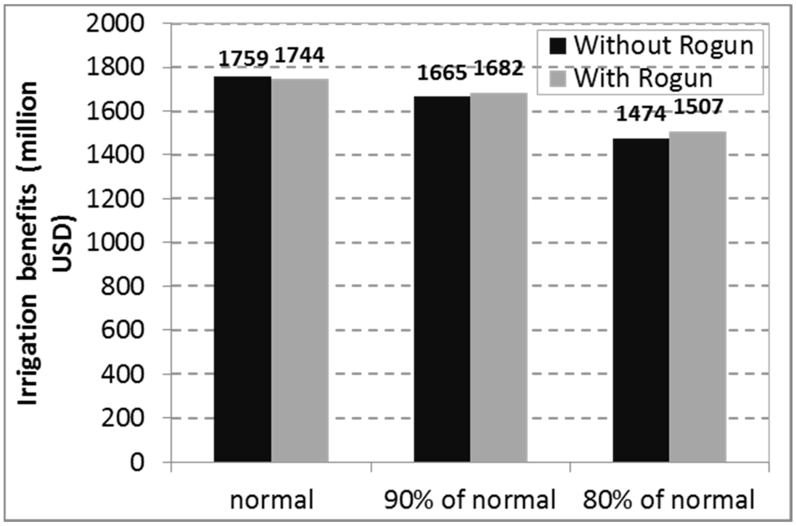
Note: Locations in Turkmenistan are in boxes with grey background, those of Uzbekistan have a white background, for Tajikistan with mixed pattern

Figure 2 Optimal monthly water releases from Nurek reservoir under different levels of water availability (normal and 80% and 90% of normal) (cooperation case)



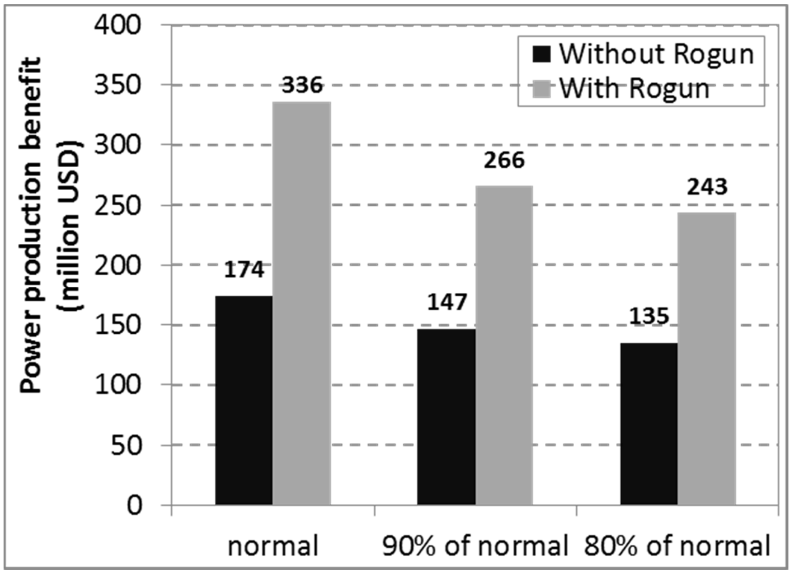
Source: Authors' calculations

Figure 3 Dam construction impact on optimal total irrigation benefits in the Amu Darya basin under different levels of water availability (cooperation case)



Source: Authors' calculations

Figure 4 Dam construction impact on optimal hydropower production benefits in the Amu Darya basin under different levels of water availability (cooperation case)



Source: Authors' calculations