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Benefits of cooperation in trans-national water-energy systems

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Abstract: Cooperation in international river basins is often challenged by upstream-downstream conflicts over water allocation. In many cases, water allocation is linked to the energy sector through hydropower. In this study, the *water value method* was used to simulate reservoir operations in an international basin given different assumptions about national priorities and regional energy cooperation. Benefits in the water sector and the power sector were compared considering both cooperative and non-cooperative behavior by national players. The approach is demonstrated for a semi-arid international river basin characterized by conflict between upstream hydropower production and downstream irrigated agriculture. A scenario assuming regional cooperation in the power sector came closest to the multi-sectoral basin cooperation benchmark and produced fewer national costs than scenarios assuming non-cooperative behavior. The results emphasize that power and water resources allocation should be viewed jointly in international river basins where upstream hydropower operations can impact downstream irrigation supplies. International cooperation in the power sector may ease upstream-downstream conflicts in these cases.

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Introduction

There are more than 260 identified international river basins world-wide which affect about 40% of the world's population (Wolf 1998). In international river basins, competition between upstream and downstream countries may have significant economic impacts. The conflict is often between irrigation and hydropower, particularly when a seasonal mismatch exists between peak demands. Prominent examples of upstream-downstream disputes on water allocation in international river basins are the Nile basin and the Aral Sea basin. Existing disputes between riparian countries in international river basins are further challenged by world population growth and climate change.

Sadoff and Grey (2002) suggested that water conflicts in international river basins could be eased by changing the perspective from sharing water itself to sharing the benefits from the use of water. The main argument is that focusing on the benefits from the use of water transforms the zero-sum game related to sharing water itself into a positive-sum game where all stakeholders could gain from cooperation. Such a 'win-win' situation implies the assumption that the river basin as a whole benefits from cooperation and that the benefits are distributed fairly (Dombrowsky 2009). Both assumptions were addressed in recent research. Arjoon *et al.* (2014), Tilmant and Kinzelbach (2012) and Whittington *et al.* (2005) assessed the value of cooperation in international river basins and found that there are significant gains from basin-wide cooperation. The equity issue of sharing benefits from cooperation has been addressed by game theory (Teasley and McKinney 2011; Wu and Whittington 2006) and an approach based on a stakeholder vision of fairness (Arjoon et al. 2016). Despite the apparent benefits, cooperation in international basins can often be obstructed by national and single-sector interests, who may be reluctant to make long-term commitments to coordinate water use because of uncertainty about future water supply and demand as well as high transaction costs (Wu and Whittington 2006).

In the last decades, hydro-economic models have been applied in various contexts to investigate the economic efficiency of water allocation plans. These models normally consider simple mass balance schemes of the river network and may use optimization according to economic criteria to establish an efficiency benchmark or simulate the economic behavior of water users (Booker et al. 2012; Harou et al. 2009). In a typical formulation, hydrologic, agronomic and economic information are used to maximize (minimize) the benefits (costs) related to different water uses such as irrigation, hydropower, and industrial and domestic water use. Recent surveys of hydro-economic models and their applications can be found in Bauer-Gottwein *et al.* (2016), Booker *et al.* (2012), Harou *et al.* (2009) and Momblanch *et al.* (2016).

In river basins where hydropower plays an important role for the regional economy, the benefit of water use for hydropower has to be included in the formulation of a hydro-economic model. A common approach is to estimate the hydropower benefit based on constant or monthly-varying exogenous electricity prices (Anghileri et al. 2013; Arjoon et al. 2014; Tilmant and Kelman 2007). However, this approach might misrepresent the value of hydropower in the energy supply mix, particularly when demands and alternative supply costs are varying. Pereira-Cardenal *et al.* (2015) demonstrated the advantages of estimating hydropower values as an output from the interaction between hydro-economic and power system models rather than an input to the hydro-economic model.

This paper describes the implementation of a hydro-economic modeling approach to estimate the benefit of power sector cooperation in international river basins. Power sector cooperation is compared to a multi-sector cooperation benchmark as well to scenarios in which national and sectoral priorities drive water allocation. The hydropower value is determined endogenously.

The proposed methodology was developed for semi-arid international river basins which are characterized by conflicting water use between irrigated agriculture and hydropower in an upstream-downstream configuration. Stochastic dynamic programming (SDP) was applied in combination with the so-called *water value method* to simulate reservoir operations and water allocation under different cooperation assumptions. The Syr Darya basin (SDRB) in Central Asia was used as a case study.

Material and Methods

The Syr Darya Basin

The Syr Darya is one of the two main tributaries to the Aral Sea in Central Asia. The basin is characterized by a semi-arid climate and a high dependence on irrigated agriculture. Agriculture represents the largest consumptive water use, while hydropower represents the largest non-consumptive water use in the basin. International water politics between the riparian countries are dominated by the conflict between water use for hydropower in the upstream countries and irrigated agriculture in the downstream countries. The conflict potential in water use for hydropower and irrigated agriculture in an upstream-downstream configuration is not unique to the Syr Darya basin but finds a parallel, for example, in the Nile basin (Wu and Whittington 2006).

About 70% of the river flow originated in the upstream part of the basin in the territory of Kyrgyzstan (Cai 1999). The vast amounts of water combined with high elevation differences in this area create highly favorable conditions for hydropower production. In fact, the biggest reservoir in the basin, Toktogul (storage: 19500 x 10^6 m^3), is located in Kyrgyzstan. Originally, the reservoir was built by the Soviet Union in order to secure water supply to agriculture in downstream regions. After the disintegration of the Soviet Union, Kyrgyzstan's winter electricity demand increased significantly due to introduction of electrical heating. Today, Kyrgyzstan, which is without significant hydrocarbon resources, is dependent on hydropower from Toktogul and the downstream Naryn Cascade during the winter months.

Conversely, irrigated agriculture in Uzbekistan and Kazakhstan depends on releases from Toktogul during the vegetation period (April-October) in dry inflow years. Irrigated agriculture is an important economic activity in both countries. Agriculture (mostly irrigated) contributes 21% of Uzbekistan's gross domestic product (GDP) (The World Bank 2012).

The river course, reservoirs and agricultural planning zones defined in this study are illustrated in **Fig. 1**.

Fig. 1. Base Map of the Syr Darya River basin. Agricultural planning zones are introduced to summarize irrigative water use in the respective area. The names of the planning zones indicate the region and the country in which they are located (CHI: Chirchic River, FER: Fergana Valley, NOR: Syr Darya Delta, SYR: Syr Darya Valley, KYR: Kyrgyzstan, TAD: Tajikistan, UZB: Uzbekistan, KAZ: Kazakhstan).

In 1992, the seasonal mismatch between upstream and downstream water demand led to the foundation of the *Interstate Commission for Water Coordination in Central Asia (ICWC)*. The commission includes representatives of the five governments of Kazakhstan, Uzbekistan, Tajikistan, Kyrgyzstan and Turkmenistan and is entrusted with interstate water resources management. Several agreements have been made in order to ensure sufficient releases from Toktogul in the vegetation period. Probably, the most important is the "Agreement on the Use of Water and Energy Resources in the Syr Darya Basin" (ICWC 1998) between Kyrgyzstan, Uzbekistan and Kazakhstan. Tajikistan joined the agreement in 1999. The agreement asks for sufficient releases from Toktogul to satisfy irrigation demands in Uzbekistan and Kazakhstan. In return, Uzbekistan and Kazakhstan should compensate Kyrgyzstan with coal, gas and electricity or their monetary equivalent in the non-vegetation period. Compliance with this agreement and all following ones is jeopardized by the uncertain value of Toktogul's storage (Teasley and McKinney 2011): Uzbekistan and Kazakhstan are willing to compensate Kyrgyzstan for releases from Toktogul in the vegetation period but they are not willing to compensate Kyrgyzstan for storing water during wet years to hedge against the risk of low inflow in the following years. Water rights trading is one potential solution discussed by the ICWC and other authorities in the Aral Sea basin to facilitate basin-wide cooperation. Bekchanov et al. (2015) show by means of hydro-economic modeling that water rights trading could increase basin-wide benefits significantly.

Besides basin-wide cooperation in the water sector for agricultural use, an opportunity for cooperation in the power sector exists through the Central Asian Power System (CAPS). It is a cluster of national grids, including the grids of Southern Kazakhstan, Uzbekistan, Tajikistan, Kyrgyzstan and Turkmenistan, operating in parallel to the United Energy System of Russia via Kazakhstan (Tomberg 2012). During the Soviet Union, this power system, composed of 83 power plants from Kazakhstan, Uzbekistan, Tajikistan, Kyrgyzstan and Turkmenistan, was run centrally from Tashkent, Uzbekistan. After the disintegration of the Soviet Union, national interests have led to misappropriation of CAPS and it went out of operation in 2009 (Tomberg 2012).

For a detailed description of the political development in the region after the disintegration of the Soviet Union, the reader is referred to the following references: Antipova *et al.* (2002), Cai (1999) and Dinar *et al.* (2007).

In summary, water and power resources allocations in the basin are tightly linked by hydropower. The dilemma of power supply deficits in Kyrgyzstan and water supply deficits for irrigated agriculture in the downstream countries is the core of the water use conflict in the Syr Darya basin.

Stochastic dynamic programming – water value method

As mentioned previously, bilateral agreements fail because the value of storing water in Toktogul during wet years to hedge against the risk of low inflow in coming years is unknown. Toktogul is the only reservoir in the basin with inter-annual storage capacity. Therefore, this study focuses on the upstream-downstream dispute on the releases from Toktogul for hydropower and irrigated agriculture. Because of the inter-annual management focus, we argue that the basin can be reasonably represented as a one-reservoir system.

Stochastic dynamic programming (SDP) in combination with the *water value method* (see Wolfgang *et al.*, (2009) and references herein) represents a method to derive optimal reservoir operating rules based on the efficient reservoir storage value as function of storage level, month of the year and inflow uncertainty. The value of stored water is determined for a discrete number of reservoir volume segments for each month of the year and inflow scenario (volume segments are denoted by index m). The calculation of water values for each reservoir volume segment is possible with SDP because the algorithm evaluates backward-moving the entire state space. That is the reason why SDP was chosen as optimization method despite its drawbacks due to the curses of dimensionality (see Giuliani et al. (2016)). For reviews on optimization methods for reservoir operation the reader is referred to Castelletti et al. (2008) and Labadie (2004).

Reservoir operation is a complex optimization problem because present releases have to be balanced against expected future benefits. These are uncertain due to uncertain future demand and supply functions, and uncertain future inflows. The uncertainty for each parameter could be described by separate state variables. However, only a limited number of state variables can be solved efficiently with SDP and therefore a choice is required (see Labadie (2004)). The uncertainty of Toktogul's inflow was considered as most important.

Similarly, each lateral inflow would have to be a state variable in the SDP optimization in order to include them as stochastic inflows in the model. The lateral inflows were included in the optimization phase as monthly average flows based on time series of the period 1960-1990. This period was chosen because data for all lateral inflows and the inflow to Toktogul were available for this period and it contains a sufficient range of wet, normal and dry inflow years to illustrate the upstream-downstream water allocation conflict. It was verified that the use of average lateral inflows does not significantly affect the resulting reservoir operation for the used model. The optimization model also considered return flows (see **Fig. 2**: Ret_FER, Ret_MID, Ret_DS), seepage losses from the river network and a minimum inflow requirement to the Northern Aral Sea. **Fig. 2** shows the conceptual river network used for the optimization.

Fig. 2. Conceptual River Network.

The optimization is based on the recursive Bellman Equation (see Equation (2.1)) (Bellman 1957). The algorithm is applied backward-moving in monthly time steps. Each objective is expressed in economic terms and the single objective function is calculated as sum of the monetary values. Consequently, the different objectives are implicitly weighted by their monetary value for society. Benefits from water allocations to agriculture are maximized and costs for power production are minimized over the planning horizon. This yields so-called water value tables for each inflow scenario. They define an efficient reservoir operating rule as a function of reservoir storage, month of the year and inflow scenario.

The inflow to Toktogul is described by a discrete first-order monthly Markov Chain. Five inflow classes are defined based on quantiles of monthly flow records of the period 1911-1998: very dry (0^{th} – 10^{th} quantile), dry (10^{th} – 30^{th}); medium (30^{th} – 70^{th}); wet (70^{th} – 90^{th}); very wet (90^{th} – 100^{th}). Discrete flows, $q_{k,t}$, are defined as mean values of the observed flows falling into the defined classes. Serial correlation is modeled by transition probabilities, p_{kl}, which express the conditional probability of moving from inflow scenario k in time step t to inflow scenario l in time step t+1. The transition probabilities are approximated by the normalized transition frequencies observed in the period 1911-1998. Statistically, the empirically derived transition probabilities approximate the underlying transition probabilities more accurate the longer the observation record. The period 1911-1998 was the longest, stationary inflow series to Toktogul available and hence the period chosen to derive the discrete first-order Markov Chain.

The state of the system is defined by Toktogul's storage volume, $v_{m,t}$, and the current month's inflow, $q_{k,t}$. The optimal value function, $\mathrm{F}_t^*(v_{m,t}, q_{k,t})$, maximizes in each time step the sum of immediate, $\mathrm{b}_t(\mathbf{x}_t, \mathbf{tpp}_t, \mathbf{usd}_t)$, and expected future benefits, $\underset{q_{k,t}}{\mathrm{E}}\left[\mathrm{F}_{t+1}^*(v_{t+1}, q_{t+1})\right]$:

$$\mathrm{F}_t^*(v_{m,t}, q_{k,t}) = \max_{\mathbf{x}_t, \mathbf{tpp}_t, \mathbf{usd}_t} \left\{ \mathrm{b}_t(\mathbf{x}_t, \mathbf{tpp}_t, \mathbf{usd}_t) + \underset{q_{k,t}}{\mathrm{E}}\left[\mathrm{F}_{t+1}^*(v_{t+1}, q_{t+1})\right] \right\} \quad (2.1)$$

immediate benefits:

$$\mathrm{b}_t(\mathbf{x}_t, \mathbf{tpp}_t, \mathbf{usd}_t) = \mathbf{mb}_{agr}^T \cdot \mathbf{x}_t - \mathbf{c}_{tpp}^T \cdot (\mathbf{tpp}_{base,t} + \mathbf{tpp}_{peak,t}) - \mathbf{c}_{usd}^T \cdot (\mathbf{usd}_{base,t} + \mathbf{usd}_{peak,t}) \quad (2.2)$$

expected future benefits:

$$\mathop{\mathrm{E}}_{q_{k,t}}\left[\mathrm{F}^*_{t+1}(v_{m,t+1},q_{t+1})\right]=\sum_{l} p_{kl}\cdot \mathrm{F}^*_{t+1}(v_{m,t+1},q_{l,t+1}) \tag{2.3}$$

where $\mathbf{x}_t$ is the vector expressing water allocations to each crop type in each planning zone, $\mathbf{mb}^T_{agr}$ represents the corresponding agricultural water value, $\mathbf{tpp}_t$ is the vector of thermal power production for all TPPs, $\mathbf{c}_{tpp}$ is the corresponding marginal cost, $\mathbf{usd}_t$ is the unserved power demand volume and $\mathbf{c}_{usd}$ stands for corresponding curtailment costs (see the following section for more explanations on the variables).

Equation (2.1) defines a one-stage optimization problem resulting in optimal releases, water and power allocations in each time step. The one-stage optimization problem is a linear program (LP) that was solved using the *cplexlp* solver by IBM®. The main constraints are the water balance at Toktogul, limits to irrigation water withdrawals, water availability at the irrigation sites, limits to releases from Toktogul, limits to thermal power production, limits to the defined unserved power demand segments and the satisfaction of observed power demand during base and peak hours. The expected future benefit function is approximated by a piece-wise linear function in order to avoid discretizing the decision variables. This approximation is also introduced as constraints to the optimization (see Equation (2.4)).

$$\begin{aligned}
&\mathop{\mathrm{E}}_{q_{k,t}}\left[\mathrm{F}^*_{t+1}(v_{t+1},q_{t+1})\right]\approx -\pi_m\cdot(v_{m,t+1}-v_{t+1})+\mathop{\mathrm{E}}_{q_{k,t}}\left[\mathrm{F}^*_{t+1}(v_{m,t+1},q_{t+1})\right] \quad \text{for m = 1,2,...,M-1}\\
&\pi_m=\frac{\mathop{\mathrm{E}}_{q_{k,t}}\left[\mathrm{F}^*_{t+1}(v_{m,t+1},q_{t+1})\right]-\mathop{\mathrm{E}}_{q_{k,t}}\left[\mathrm{F}^*_{t+1}(v_{m,t+1},q_{t+1})\right]}{v_{m+1,t+1}-v_{m,t+1}}
\end{aligned} \tag{2.4}$$

where m is the index for the discretized storage volumes and M is the index indicating the maximum storage volume.

Water values, WV [USD/m^3], for each reservoir level correspond to the shadow prices of the water balance constraint at Toktogul (see Equation (2.5)).

$$WV_t = \frac{\partial F_t^*}{\partial v} \approx \frac{\Delta F_t^*}{\Delta v} \tag{2.5}$$

In the presented study, the storage discretization is chosen to ensure a good approximation of the derivative. Nevertheless, the authors acknowledge that state-of-the-art linear programming solvers provide shadow prices as output variables and hence the water values could be obtained in each step directly from the solver. The algorithm is run for several years until the water values are no longer dependent on the end point condition.

System operation is simulated forward-moving using historical inflow time series for the period 1960-1990 instead of average lateral inflows used during the optimization. Based on the observed inflow and storage volume in time step t, solving the linear program in Equation (2.1) results for each time step in releases, water and power allocations that maximize immediate and expected future benefits. The expected future benefit function is estimated from the water value tables. The slopes of the expected future benefit function are given by the weighted average of WV_{t+1} weighted with the respective transition probabilities.

Hydro-Economic Input Data

Unless otherwise noted, all input data used in this study are from data collection executed during the Aral Sea Basin Economic Allocation Model (BEAM) project conducted by the World Bank in 2013. The data were obtained by personal communication with Dr. Benoit Blarel of the World Bank on 13.11.2017.

Hydrological input data

The river runoff pattern in the SDRB is correlated to snow accumulation during the previous winter season (October-March) and the extent of glaciers in the Tien Shan mountains (Oberhänsli et al. 2011). As a consequence, the river runoff is highly seasonal. About 70-80% of the total annual river flow occurs in the summer season (April-September) (see **Fig. 3**).

Fig. 3. Monthly average inflows to Toktogul of the period 1911 – 1998.

Agricultural input data

Fifteen crop types are considered in the model. Cotton and wheat are the most frequently grown crops in the basin. Data for crop evapotranspiration, effective rainfall, crop area, leaching volumes, and seepage losses from channels and at field level are available. Seepage losses from channels transporting the river water to the agricultural site and at field level are significant in the basin (both approximately 30% according to stakeholder workshops conducted during the BEAM project and Bekchanov et al. (2016)). They are used as proxy for the basin efficiency which defines the ratio between water diverted from the river and water that actually reaches the crop. Monthly irrigation water requirements for each crop type in each planning zone are calculated with these input data. It is assumed that the crop area distribution in the basin is constant over the planning horizon.

The total average annual river discharge is about 40% less than total annual irrigation water requirement. This underlines the water scarcity in the basin. Uzbekistan has by far the highest irrigation water demand; especially for cotton and wheat. The Uzbek annual irrigation water demand is more than 3.5 times larger than the second highest demand of Kazakhstan.

Detailed demand functions for agricultural users in the Syr Darya basin are not available and therefore constant marginal benefits are assumed. Consequently, average and marginal water values are identical. Marginal agricultural water values are calculated with the residual imputation method based on the production exhaustion theorem (Young and Loomis 2014). Input costs for labor, seeds, fertilizers, pesticides and capital (excluding the irrigation system) are considered. When comparing benefits derived from water allocations to competing uses, it is important to compare at-source values instead of at-site values. At-site values are usually larger than at-source values because they value the water which arrives at the user site neglecting losses and conveyance costs. Conveyance costs could not be included due to data deficiencies but losses occurring on the way from the river to the crop were included. **Fig. 4** lists the resulting estimates of agricultural at-source water values. In the optimization model, it is assumed that these water values are constant throughout the growing season even though the authors are aware that agricultural water values depend on the crop yield – water supply relationship. However, it is argued that this assumption does not significantly affect the comparative valuation of different cooperation scenarios and reduces the complexity of the SDP setup.

Fig. 4. Estimated agricultural at-source water values, (USD/m3), for each crop type and planning zone in the Syr Darya basin (alf: alfalfa, cot: cotton, tmt: tomato, wht: wheat, tgr: table grapes, shv: cucumber, ric: rice, pot: potato, sbt: sugar beet, stf: stone fruits, mln: melon, mng: mango, mzf: maize for fodder, mzg: maize for grain). It should be noted that cotton is among the low value crops.

Power system model

The power system of Uzbekistan, Kyrgyzstan and a hypothetical reestablished joint power system between the two is included in the optimization model in order to evaluate the potential impact of power systems on international river basin cooperation. Approximately 88% of Uzbekistan's power supply is based on thermal power production (World Energy Council 2007). The Uzbek power system is modeled with 10 thermal power plants (TPP). The Kyrgyz power system is assumed to be composed of one TPP and hydropower from Toktogul and the Naryn Cascade. 90% of Kyrgyz power supply is based on hydropower of which 97% are concentrated in the Naryn Cascade (Antipova et al. 2002).

The power system model is set up as simple as possible and as complex as needed to serve the purpose. A merit order approach (Wangsteen 2007) is chosen which assumes that producers have constant marginal costs and to satisfy the power demand, production is scheduled from cheapest to most expensive producer. Variable efficiency rates, transmission and security constraints, and costs such as start-up costs are neglected.

An elastic demand function is used to model cost efficient allocation of the power resources in Uzbekistan and Kyrgyzstan. For both countries, an elastic demand function is estimated based on observed demand (see **Fig. 5**), the electricity tariff and price elasticity. Electricity tariffs are found to be 52.5 USD/MWh and 25.2 USD/MWh in Uzbekistan and Kyrgyzstan, respectively. The price elasticity is assumed to equal -0.2 in Uzbekistan and -0.15 in Kyrgyzstan. For linearization purposes, the demand function is divided into 5% segments of the observed demand. Each segment was associated with a constant willingness to pay.

Fig. 5. Observed monthly power demand in Uzbekistan and Kyrgyzstan during base and peak hours, (GWh/month).

In the optimization, the estimated power demand function is implemented as curtailment source with a marginal cost corresponding to the willingness to pay for the respective power segment. In other words, the observed power demand can be satisfied by power production and 5% curtailment increments at a certain cost. Demand satisfaction is considered separately for base and peak demand hours in one month. If monthly demand was simply averaged, parts of the supply function needed during peak demand hours would be neglected which might influence the hydropower value and reservoir operation significantly. In Kyrgyzstan, power demands peak in the winter months due to climate. Power demand in Uzbekistan peaks during summer months because of electricity requirements for the extensive irrigation system.

Hydropower

From the hydropower perspective, the potential yield of Toktogul and Naryn cascade combined is almost 3 times higher than the next highest potential yield at the Chirchik reservoir (Toktogul and Naryn Cascade: 889 MWh/10^6 m^3; Chirchik: 322 MWh/10^6 m^3). These figures demonstrate that the joint system of Toktogul and Naryn Cascade dominates the Syr Darya basin from the storage and hydropower perspective.

For monthly reservoir operation, the storage volume of the Naryn Cascade is negligible compared to releases from Toktogul. Thus, it is assumed that the Naryn Cascade always produces hydropower at maximum head. A constant power yield is assumed for Toktogul and Naryn Cascade combined ($y_{hp} = 860$ MWh/10^6 m^3) in order to reduce complexity of the SDP setup. It corresponds to the medium storage volume of Toktogul, 12500 10^6 m^3. The error due to this assumption should be reasonably small because the power yield for Toktogul and Naryn Cascade combined varies only by 17% over the storage range of Toktogul. At the chosen yield the flow capacity of the Naryn Cascade is the binding flow constraint and thus it is used as maximum release volume for the combined system.

Hydropower production costs are negligible compared to thermal power production and thus hydropower operational costs are assumed to be zero.

Experiment Setting

The simulation approach to demonstrate the impact of collaboration in the power sector and the agricultural sector on international river basin cooperation can be summarized in two steps:

1. Efficient reservoir operating rules (water value tables) for Toktogul are derived using SDP in combination with the *water value method*.
2. Based on the water value tables, optimal reservoir releases, water allocations, power allocations and related benefits are simulated and compared.

In six different cooperation scenarios, Toktogul releases and water allocations are optimized either on the national or the basin scale. Three different operating objectives are considered: (1) benefits in the agricultural sector only (SSAgr) (see Equations (2.9)), (2) costs in the power sector only (SSPower) (see Equations (2.7) and (2.8)) and (3) difference between benefits in the agricultural sector and costs in the power sector (MS) (see Equations (2.2) and (2.6)). Hence, scenario specific steady-state water value tables are determined. These are used to simulate optimal reservoir releases, water allocations, power allocations and corresponding benefits for the different scenarios. The main characteristics of the scenarios are summarized in **Table 1** and the following sections. The performance of the different scenarios is evaluated based on the cumulative difference between basin-wide benefits in the agricultural sector and costs in the power sector over the simulation period.

Scenario A: Basin_MS

The basin-multi-sector scenario optimizes the operation of Toktogul to maximize the difference between basin-wide agricultural benefits and power generation costs for a reestablished power grid between Kyrgyzstan and Uzbekistan (see Equation (2.2)). This implies that monthly power demand of Kyrgyzstan and Uzbekistan is summed and can be satisfied with power production from both countries.

The basin_MS scenario represents a theoretical benchmark for multi-sector, basin-wide cooperation in the Syr Darya basin.

Scenario D: National_MS

Toktogul releases are optimized to maximize agricultural benefits and to minimize power generation costs in Kyrgyzstan. Water allocation to downstream agricultural sites are determined sequentially with linear programs (LPs, see Equation (2.1) considering only immediate, national agricultural benefits) given the remaining water availability after Kyrgyzstan has implemented unilaterally optimal reservoir release decisions. The Kyrgyz and the Uzbek power system are considered separately. Consequently, the power generation in Uzbekistan is modeled with a linear program which minimizes generation costs (see Equation (2.1) considering only immediate, national power generation costs). Equation (2.6) shows the corresponding objective function.

$$b_t = \mathbf{mb}^T_{KYR,agr} \cdot \mathbf{x}_{KYR,agr,t} - \mathbf{c}^T_{KYR,tpp} \cdot (\mathbf{tpp}_{KYR,base,t} + \mathbf{tpp}_{KYR,peak,t}) - \mathbf{c}^T_{usd} \cdot (\mathbf{usd}_{KYR,base,t} + \mathbf{usd}_{KYR,peak,t}) \quad (2.6)$$

The national_MS scenario stands for national appropriation of the water resources and the case that Kyrgyzstan optimizes Toktogul for the agricultural and the power sector.

Scenario B: Basin_SSPower

A reestablished power grid between Kyrgyzstan and Uzbekistan is considered which implies that monthly power demand of both countries can be satisfied with power resources from both countries. This hypothetically shared power grid is essentially the same as a regional power market. The objective function only contained power generation costs (see Equation (2.7)). Given optimal reservoir release decisions with respect to the joint power system, water allocation to agriculture in each time step is determined sequentially in each country with LPs (see Equation (2.1) considering only immediate, national agricultural benefits).

$$\mathrm{b}_t = -\mathbf{c}_{tpp}^T \cdot (\mathbf{tpp}_{base,t} + \mathbf{tpp}_{peak,t}) - \mathbf{c}_{usd}^T \cdot (\mathbf{usd}_{base,t} + \mathbf{usd}_{peak,t}) \tag{2.7}$$

The basin_SSPower scenario is introduced to evaluate the impact of cooperation in the power sector on water resources allocation in the basin.

Scenario E: National_SSPower

For evaluation of cooperation in the power sector the national_SSPower scenario optimizes Toktogul releases only with respect to power generation costs in Kyrgyzstan. The Uzbek power system is independent and the water allocation to agriculture in the riparian countries is determined sequentially as in the basin_SSPower scenario.

$$\mathrm{b}_t = -\mathbf{c}_{KYR,tpp}^T \cdot (\mathbf{tpp}_{KYR,base,t} + \mathbf{tpp}_{KYR,peak,t}) - \mathbf{c}_{usd}^T \cdot (\mathbf{usd}_{KYR,base,t} + \mathbf{usd}_{KYR,peak,t}) \tag{2.8}$$

Scenario C: Basin_SSAgr

The basin_SSAgr scenario optimizes operation of Toktogul only with respect to agricultural benefits. Based on the resulting releases the power generation in Kyrgyzstan is scheduled with a linear program (see Equation (2.1) considering only immediate, national power generation costs).

The Uzbek power system is modeled as in the national_MS scenario. In case the power generated from Toktogul releases exceeds the Kyrgyz power demand, it is assumed that Kyrgyzstan receives a benefit from exporting this power at a price of 0.046 USD/kWh (Peyrouse 2009). This benefit is subtracted from the thermal power production costs in Kyrgyzstan during the simulation phase. It is not considered in the objective function (see Equation (2.9)).

$$\mathrm{b}_t = \mathbf{mb}_{agr}^T \cdot \mathbf{x}_t \tag{2.9}$$

In case the power generated from Toktogul releases is less than the Kyrgyz power demand, unserved power demand costs (USD Costs) are accumulated outside of the objective function and considered in the performance indicator, PF^{ind}, of the scenario.

Scenario F: National_SSAgr

The national counterpart of the basin_SSAgr scenario optimizes Toktogul releases only with respect to agricultural benefits in Kyrgyzstan. However, a preliminary analysis showed that the discrete inflows to Toktogul and monthly average flows from the lateral sources available to FER_KYR (Src_NAR, Src_AND and Src_KAR) provide sufficient water to fully supply the comparably low irrigation water demand in each month and inflow scenario. Thus, no specific operation of Toktogul would be needed in this scenario and it would function as run-through reservoir. In reality, it is no option to operate Toktogul as run-through reservoir and therefore this scenario is not considered in the comparison.

Results and Discussion

Water Value Tables

The five optimization scenarios result in steady-state water value tables which define optimal reservoir operation according to the different objective functions (see Equation (2.2) and Equations (2.6) to (2.9)). Contour plots of the tables are shown in **Fig. 6**. The tables show that the value of stored water increases in each month from top to bottom of the reservoir and from the *very wet* to the *very dry* inflow scenario. In months where it is important to store water for future releases the water value increases compared to values in other months at the same storage level. In some water value tables a drop of contour lines can be observed in June. This reflects that June is the highest inflow month.

Almost identical water value tables are found for the national_MS and the national_SSPower scenario. This emphasizes that specific operation of Toktogul is needed to satisfy Kyrgyz power demand while it is not for the agricultural sector. **Fig. 6** illustrates a marked increase in the cost of releasing water prior to the months with highest power demand (Nov-Mar).

Fig. 6. Contour plots of the steady-state water value tables (water values in USD/m^3) for the basin_MS scenario (A), the basin_SSPower scenario (B), the basin_SSAgr scenario (C), the national_MS scenario (D) and the national_SSPower scenario (E). The contour lines (blue lines) represent reservoir levels with the same water value (number on contour line). These values indicate the optimal cost for water released from the respective volume segment.

The water value tables of the basin_SSAgr scenario reflect the seasonality of irrigation water requirements; water values are highest prior to the months with highest demand (Jun-Aug). The comparably low water values indicate that, in the efficient allocation, demand satisfaction of high value crops such as fruits and vegetables does not depend on the operation of Toktogul. Water supply to high demand and low value crops such as cotton seems to dominate the water value tables for the basin_SSAgr scenario.

The water values for the basin_SSPower scenario are significantly higher than the values found for the basin_SSAgr scenario indicating that hydropower production from Toktogul is more valuable than releases for downstream agriculture. It turns out that the water values for this scenario equal 0.0731 USD/m^3 over large ranges of Toktogul's storage. This value corresponds to the marginal power production cost of the Uzbek thermal power plants 3 and 4. Both plants have large production capacities compared to more expensive power sources. It seems that hydropower from Toktogul can substitute thermal power production by more expensive producers for most reservoir levels in each month. However, the water values for this scenario also reveal the importance of saving water for winter power demands.

Water values of the basin_MS scenario are the highest because the scenario considers basin-wide agricultural benefits and power production costs from the joint power system between Uzbekistan and Kyrgyzstan. The seasonality introduced by irrigation water demands almost disappears because of joint power demands where seasonal differences are lower. From the basin perspective, releases from Toktogul seem to be most valuable from December to August.

Comparison of multi-sectoral cooperation scenarios

The water value tables in **Fig. 6** are used to simulate the operation of Toktogul for the period 1960-1990. Given the scenario specific operation of Toktogul, benefits in the agricultural sector and costs in the power sector are determined as described in the Materials and Method section. The performance indicator, PF^{ind}, was introduced which expresses the annual difference between basin-wide benefits in the agricultural sector and costs in the power sector.

$$PF_n^{ind} = \sum_{t=Jan}^{Dec} \mathbf{mb}_{agr}^T \cdot \mathbf{x}_t^* - \mathbf{c}_{tpp}^T \cdot (\mathbf{tpp}^*{}_{base,t} + \mathbf{tpp}^*{}_{peak,t}) - \mathbf{c}_{usd}^T \cdot (\mathbf{usd}^*{}_{base,t} + \mathbf{usd}^*{}_{peak,t}) \tag{3.1}$$
$$\text{for n} = 1960, 1961, \ldots, 1990$$

where $\mathbf{x}_t^*$, $\mathbf{tpp}_t^*$ and $\mathbf{usd}_t^*$ are basin-wide water allocation to agriculture, thermal power production and unserved power demand, respectively, determined during the simulation phase for the different scenarios (see Materials and Method section).

It should be noted that optimal operation decisions are not unique in cases where water values are identical for different storage levels (see for example the basin_SSPower scenario). In these cases, the simulation shows only one optimal solution for the system operation. Priority criteria could be introduced to select certain candidates of the possible optimal solutions. This study did not investigate this.

The cumulative performance indicator and national costs for the different cooperation scenarios are compared. **Fig. 7** shows the cumulative performance indicator for all scenarios.

Fig. 7. Cumulative performance indicator.

It can be seen that the theoretical benchmark scenario, basin_MS scenario, accumulates over the simulation period at least 15 billion USD more than all remaining scenarios. This gives an estimate for the potential value of international cooperation in the agricultural and the power sector. The national_MS scenario accumulates at the end of the simulation period only 7 million USD more than the national_SSPower scenario. It is expected from the water value tables that these two scenarios result in almost identical benefits for the basin. The basin_SSAgr scenario performs worst with respect to the difference in basin-wide benefits in the agricultural sector and costs in the power sector. It accumulates 1.72 billion USD less than the national_MS scenario. The basin_SSPower scenario comes closest to the multi-sectoral basin cooperation benchmark. It outperforms the basin_SSAgr scenario by 7.93 billion USD over the simulation period.

The cause of the difference in cumulative performance indicators becomes clearer when national costs due to water deficits in the agricultural sector, thermal power production and unserved power demand are analyzed.

The differences in national costs in Tajikistan and Kazakhstan are one order of magnitude lower than the differences in Kyrgyzstan and Uzbekistan. This finding confirms that Toktogul's operation with respect to the water use in Kyrgyzstan and Uzbekistan is key to the upstream-downstream conflict in the Syr Darya basin from an economical perspective. Thus, the discussion on national costs focuses on the differences between scenarios in Kyrgyzstan and Uzbekistan (see **Table 2**).

The negative thermal production cost in Kyrgyzstan for the basin_SSAgr scenario originates from Kyrgyzstan's export of excess hydropower in the summer months (see Materials and Method section). While these export benefits could be lower or higher with changing export prices and agreements, the values show that Kyrgyz benefits due to exported electricity are low compared to differences in agricultural shortage costs in Uzbekistan and unserved power demand costs in Kyrgyzstan. Therefore, it is concluded that the interpretation of the scenario comparison does not depend on the value of the electricity export price.

As expected, the two national scenarios succeeded to lower unserved power demand costs in Kyrgyzstan significantly. This is the main reason why these two national scenarios result in increased cumulative performance indicators compared to the basin_SSAgr scenario.

The basin_SSPower scenario creates for all countries combined less agricultural shortage costs than the national_MS and the national_SSPower scenario. These two scenarios show lower agricultural shortage costs only in Kyrgyzstan because substitution of some thermal power production by hydropower during the vegetation period seems to be beneficial from the national perspective.

The cumulative performance indicator of the basin_SSPower scenario is closest to the indicator of the basin_MS scenario. It uses hydropower from Toktogul to keep unserved power demand costs in Kyrgyzstan on a comparably low level and at the same time to lower thermal power production costs in Uzbekistan. The increase of agricultural shortage costs in Uzbekistan is markedly lower than saved unserved power demand costs (compare basin_SSPower and basin_SSAgr). The lower value of agricultural shortage costs in Uzbekistan compared to thermal power production costs in Uzbekistan and unserved power demand costs in Kyrgyzstan explains the discrepancy between the basin_SSPower and basin_SSAgr scenario.

The basin_MS scenario allocates electricity from Uzbek thermal power production to Kyrgyzstan in the winter months in order to reduce unserved power demand costs. During the vegetation period, releases from Toktogul are used to limit agricultural shortage costs in all countries, reduce thermal power production and unserved power demand costs in Uzbekistan. In comparison to previous hydro-economic studies in the SDRB, this scenario also confirms the potential value of irrigation benefits in the basin. Cai et al. (2002) and (2003) produced a benchmark for hydro-economic model results in the SDRB. In the optimized case, Cai et al. (2003) derive an annual irrigation benefit of 3.26 billion USD for the entire basin. In the basin_MS scenario, the annual average irrigation benefit lies in the same order of magnitude with 4.83 billion USD. The irrigation benefit in this study might be different compared to Cai et al. (2003) because more crop types were considered explicitly, the impact of salinity on crop yields was not considered, inflows to Toktogul were described stochastically rather than assuming an average inflow year and releases for hydropower are based on an endogenous hydropower value.

While these results illustrate potential benefits from basin cooperation similar to previous studies (Arjoon et al. 2014; Teasley and McKinney 2011; Tilmant and Kinzelbach 2012; Whittington et al. 2005), they also highlight obstacles to bilateral agreements. The theoretical benchmark for basin cooperation in the agricultural and power sector (basin_MS scenario) generates the lowest annual national costs only for Uzbekistan. Kyrgyzstan loses on average 239.7 million USD/year in the basin_MS scenario compared to national appropriation of Toktogul's storage capacity (national_MS scenario). Uzbekistan advocates an operation of Toktogul that satisfies the national irrigation demand which would correspond to an operation similar to the basin_SSAgr scenario. The comparison of national costs in the basin_SSAgr and national_MS scenario shows the potential stakes of Kyrgyzstan and Uzbekistan in bilateral negotiations. Uzbekistan saves on average 568 million USD/year and Kyrgyzstan loses on average 640.7 million USD/year in the basin_SSAgr scenario compared to the national_MS. Together with the aversion of compensating Kyrgyzstan for storing water in wet years to hedge for following dry years, these values emphasize the reason for the upstream-downstream dispute on Toktogul's operation. The basin_SSPower scenario seems to be a compromise between the national_MS and basin_SSAgr scenario. It lowers the average annual costs for both Uzbekistan and Kyrgyzstan with respect to the national_MS and basin_SSAgr scenario, respectively. Even agricultural shortage costs in Uzbekistan are reduced in the basin_SSPower scenario compared to the national_MS scenario.

These results are promising because cooperation in the power sector is traditionally not considered by river basin commissions which focus typically on the water sector. Based on the presented case study, regional power cooperation can achieve some of the benefits from multi-sectoral basin cooperation in international river basins characterized by an upstream-downstream conflict on water allocation to irrigated agriculture and hydropower. Nevertheless, it should be noted that the benefits from the different cooperation scenarios can only ease the water-energy conflict in the region if they are shared in an equitable manner.

Conclusion

Stochastic dynamic programming in combination with the *water value method* was used to derive reservoir operating rules for Toktogul Reservoir under different assumptions about international cooperation in both the water and energy sectors. These operating rules were then used to simulate basin water use and associated economic values in order to estimate the costs and benefits of different levels of cooperation. The water value method provides steady-state water value tables by maximizing the sum of immediate and expected future benefits. The tables define optimal reservoir releases as a function of storage level, month of the year and inflow scenario. This approach is useful for defining optimal reservoir operating rules under different assumptions about international cooperation, particularly when the value of inter-annual reservoir storage is key to a conflict between upstream and downstream riparian states.

A comparison of multi-sectoral cooperation scenarios was performed to assess the impact of cooperation in the power sector and the agricultural sector on basin-wide benefits. International cooperation in the power sector came closest to the multi-sectoral basin cooperation benchmark. The difference of basin-wide benefits in the agricultural sector and costs in the power sector was 510 million USD/year less than for the multi-sectoral basin cooperation scenario. International cooperation in the agricultural sector alone performed by 774 million USD/year worse than the basin-wide scenario for multi-sectoral cooperation. The national multi-sector and power sector scenario generated almost identical benefits. Both outperformed the scenario for basin cooperation in the agricultural sector by 57 million USD/year. The main cause for the scenario differences was identified to be high thermal power production costs in Uzbekistan and unserved demand costs in Kyrgyzstan compared to agricultural shortage costs in Uzbekistan. From a national perspective, Kyrgyzstan achieved lowest annual costs in the national multi-sector scenario and Uzbekistan in the basin-wide scenario for multi-sectoral cooperation followed by the scenario of international cooperation in the agricultural sector. Regional power cooperation reduced national costs in Kyrgyzstan compared to the basin cooperation scenarios and in Uzbekistan compared to the national appropriation of Toktogul's storage capacity. Hence, regional power cooperation can potentially ease international water-energy conflicts. This represents a practical alternative to the traditional approach of river basin commissions which focus typically on the water sector. It is essential to view power and water resources allocation jointly in international river basins where the power and the agricultural sector are tightly linked by hydropower. International cooperation in the power sector may ease upstream-downstream conflicts in these cases.

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Table 1. Summary of assumptions for different operating objectives.

	National	Basin
SSPower	Toktogul's operation is optimized for Kyrgyz power sector (see scenario E)	Toktogul's operation is optimized for the regional power market between Kyrgyzstan and Uzbekistan. (see scenario B)
SSAgr	Toktogul's operation is optimized for Kyrgyz agriculture sector. (see scenario F)	Toktogul's operation is optimized for basin-wide agricultural water use. (see scenario C)
MS	Toktogul's operation is optimized for Kyrgyz agriculture and power sector (see scenario D).	Toktogul's operation is optimized considering basin-wide benefits from agricultural water use and costs for the regional power market between Kyrgyzstan and Uzbekistan. (see scenario A)

Table 2. Average annual national costs, [10^6 USD/year], in Kyrgyzstan and Uzbekistan due to water deficits in the agricultural sector (Shortage Cost), thermal power production (TPP Cost), unserved power demand (USD Cost) and both sectors combined (Total).

	Kyrgyzstan				Uzbekistan			
	Shortage Cost	TPP Cost	USD Cost	Total	Shortage Cost	TPP Cost	USD Cost	Total
basin_MS	27.1	41.4	212	281	161	2670	481	3312
basin_SSPower	2.54	41.4	198	242	661	2650	517	3828
basin_SSAgr	29.8	-173	825	682	148	2990	517	3655
national_MS	0.0296	31.1	10.2	41.3	716	2990	517	4223
national_SSPower	0.218	31.6	9.6	41.4	716	2990	517	4223

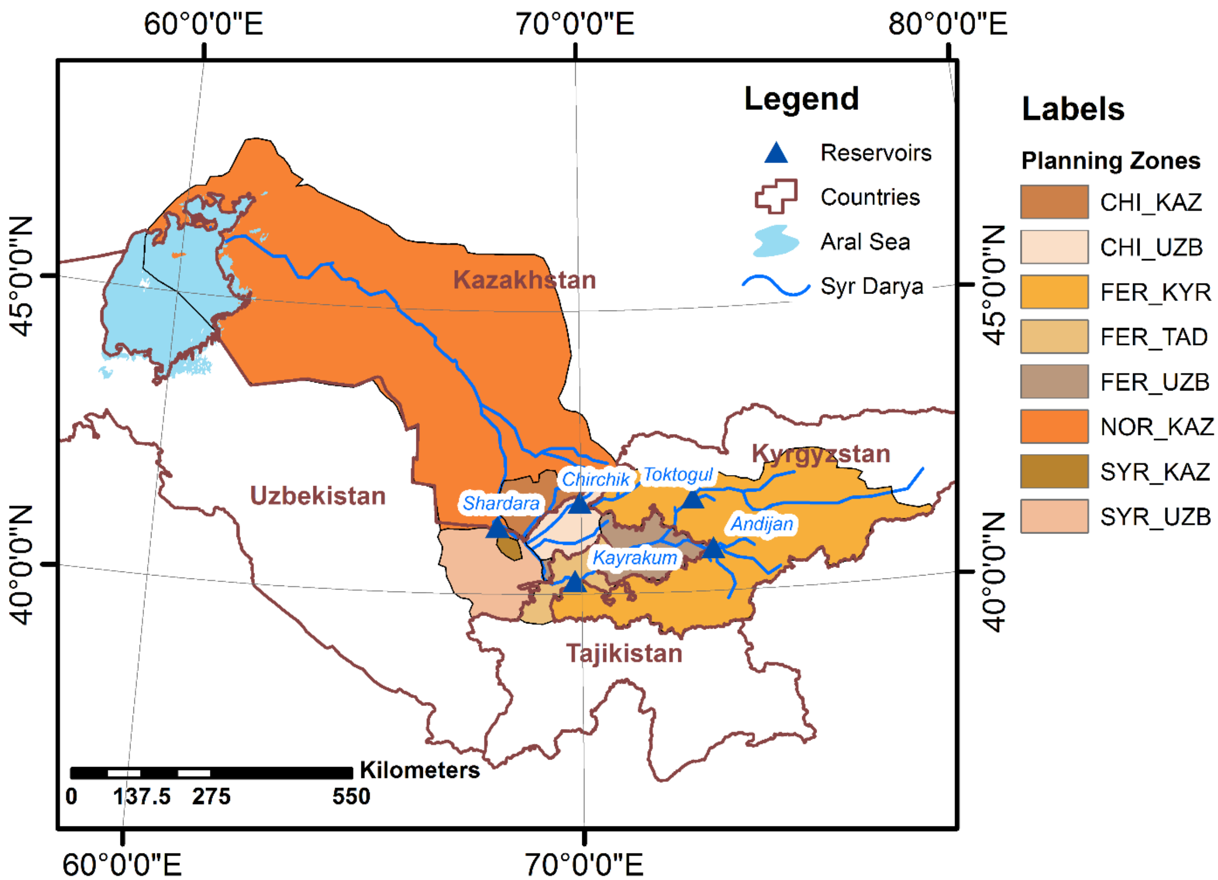

Fig. 1. Base Map of the Syr Darya River basin. Agricultural planning zones are introduced to summarize irrigative water use in the respective area. The names of the planning zones indicate the region and the country in which they are located (CHI: Chirchic River, FER: Fergana Valley, NOR: Syr Darya Delta, SYR: Syr Darya Valley, KYR: Kyrgyzstan, TAD: Tajikistan, UZB: Uzbekistan, KAZ: Kazakhstan).

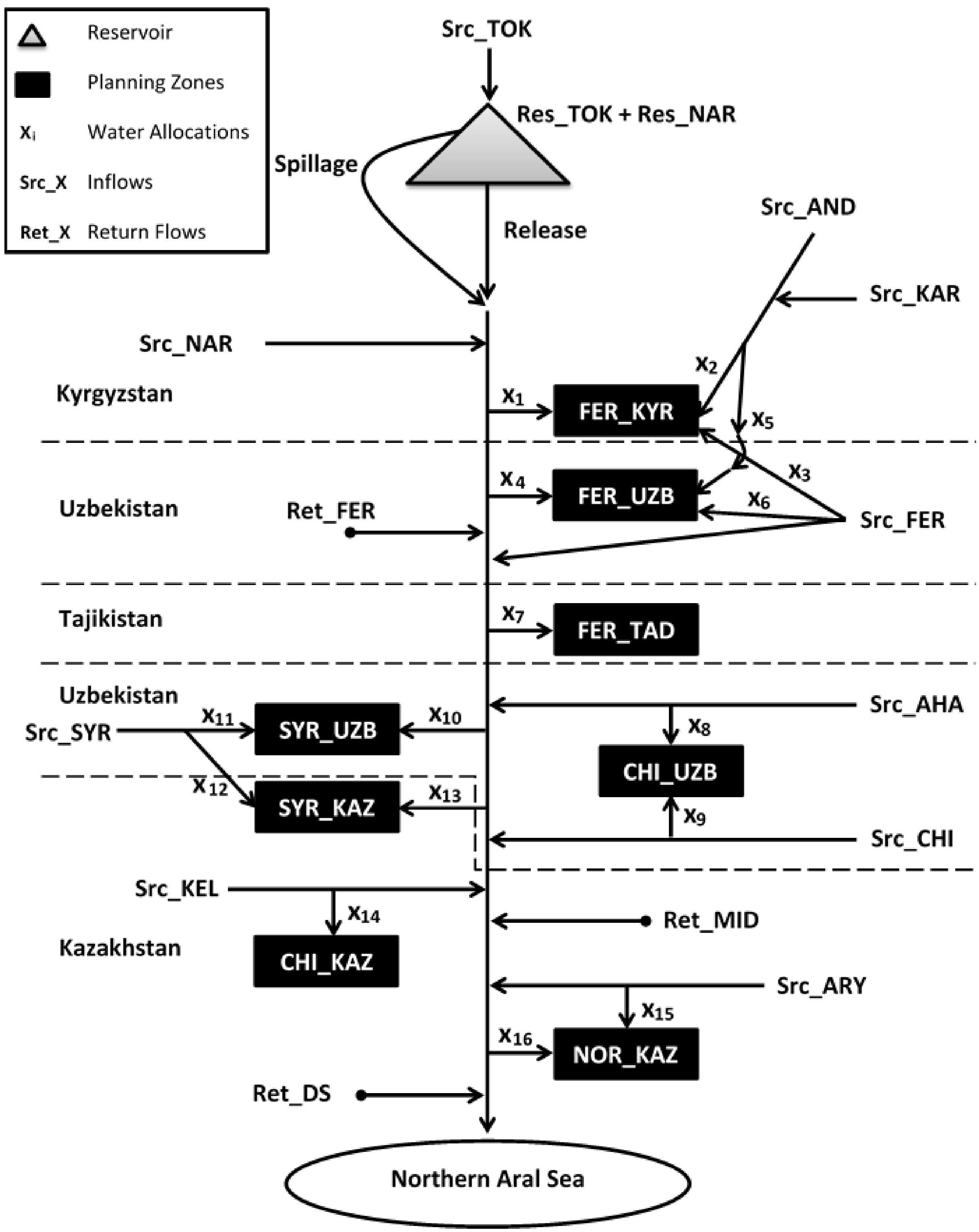

Fig. 2. Conceptual River Network.

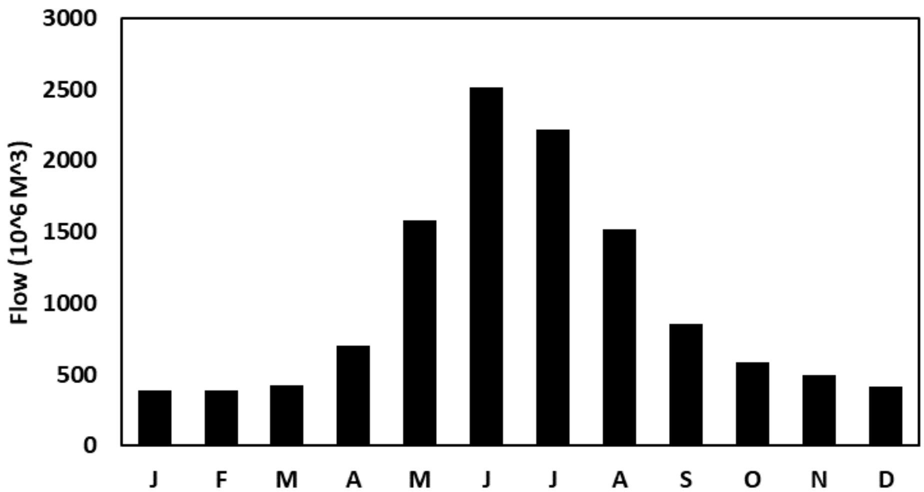

Fig. 3. Monthly average inflows to Toktogul of the period 1911 – 1998.

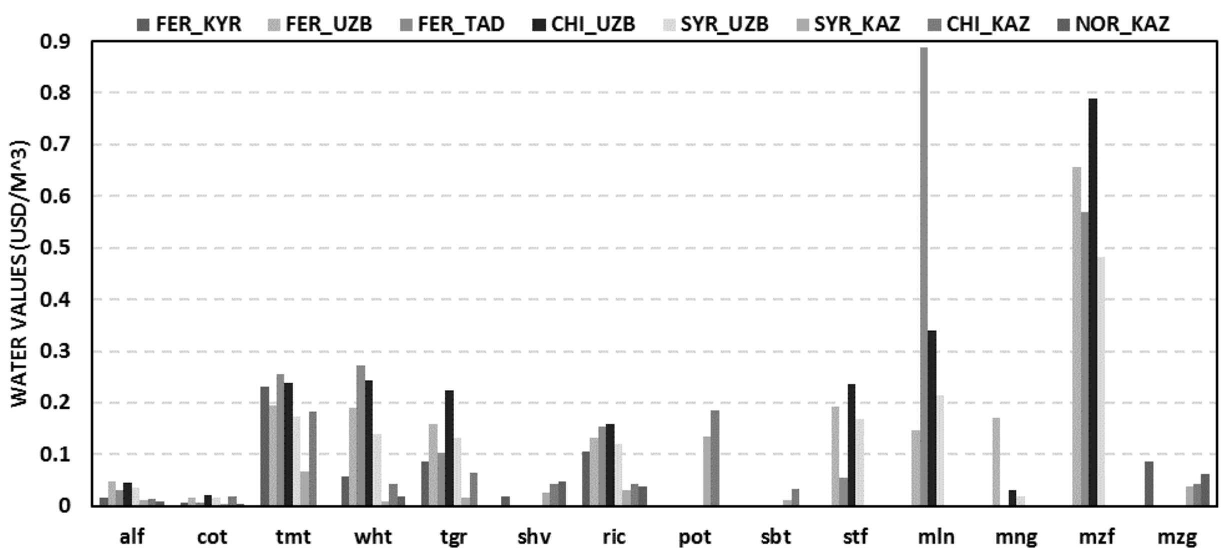

Fig. 4. Estimated agricultural at-source water values, (USD/m3), for each crop type and planning zone in the Syr Darya basin (alf: alfalfa, cot: cotton, tmt: tomato, wht: wheat, tgr: table grapes, shv: cucumber, ric: rice, pot: potato, sbt: sugar beet, stf: stone fruits, mln: melon, mng: mango, mzf: maize for fodder, mzg: maize for grain). It should be noted that cotton is among the low value crops.

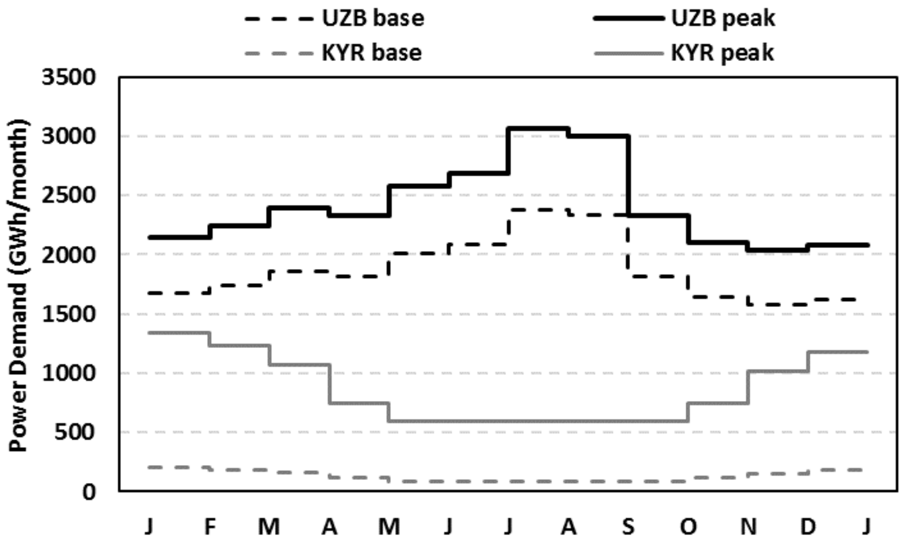

Fig. 5. Observed monthly power demand in Uzbekistan and Kyrgyzstan during base and peak hours, (GWh/month).

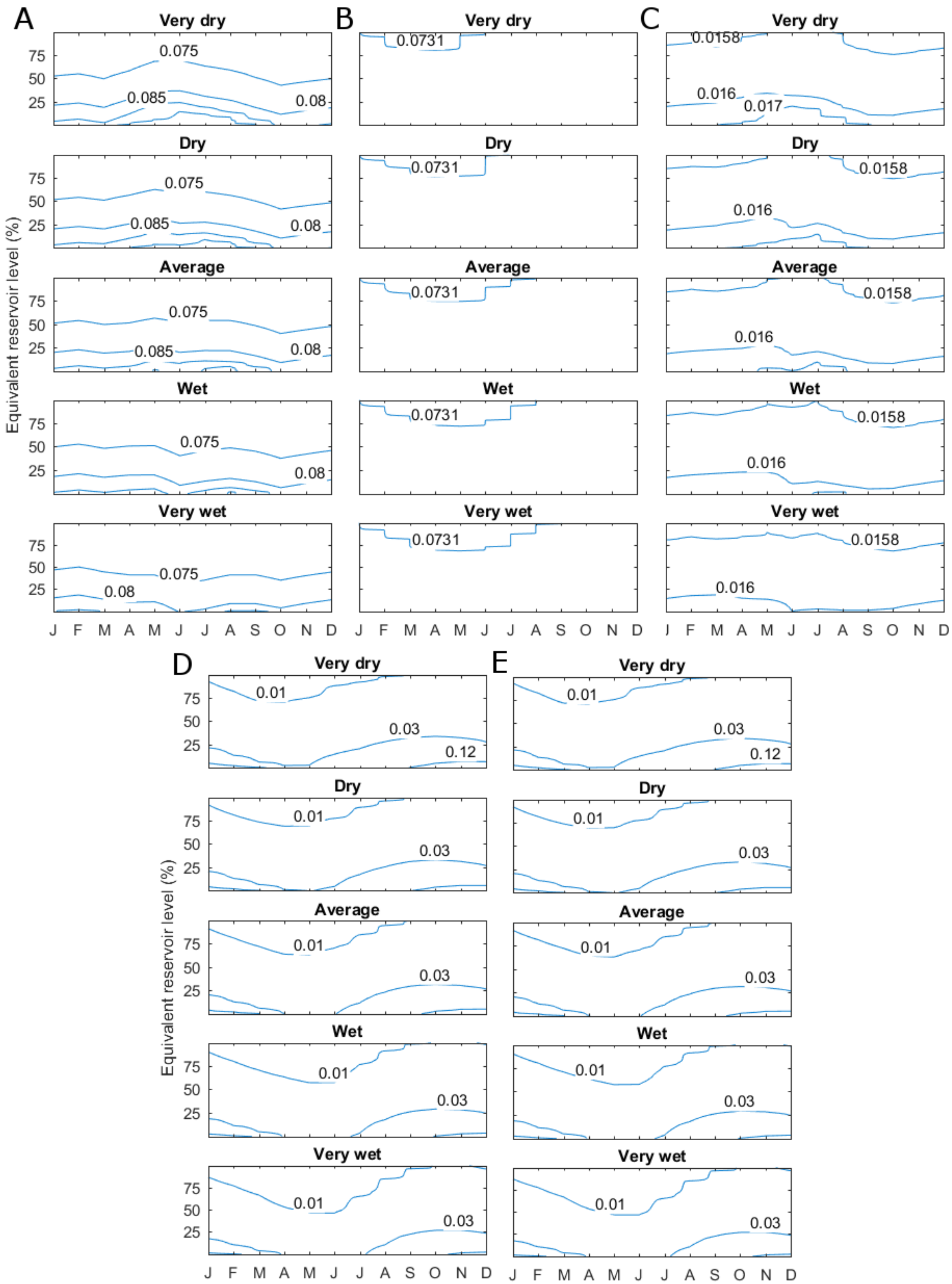
A
B
C
Very dry
Dry
Average
Wet
Very wet
0.075
0.085
0.08
0.0731
0.0158
0.016
0.017
Equivalent reservoir level (%)
75
50
25
J F M A M J J A S O N D
D
E
0.01
0.03
0.12

Fig. 6. Contour plots of the steady-state water value tables (water values in USD/m^3) for the basin_MS scenario (A), the basin_SSPower scenario (B), the basin_SSAgr scenario (C), the national_MS scenario (D) and the national_SSPower scenario (E). The contour lines (blue lines) represent reservoir levels with the same water value (number on contour line). These values indicate the optimal cost for water released from the respective volume segment.

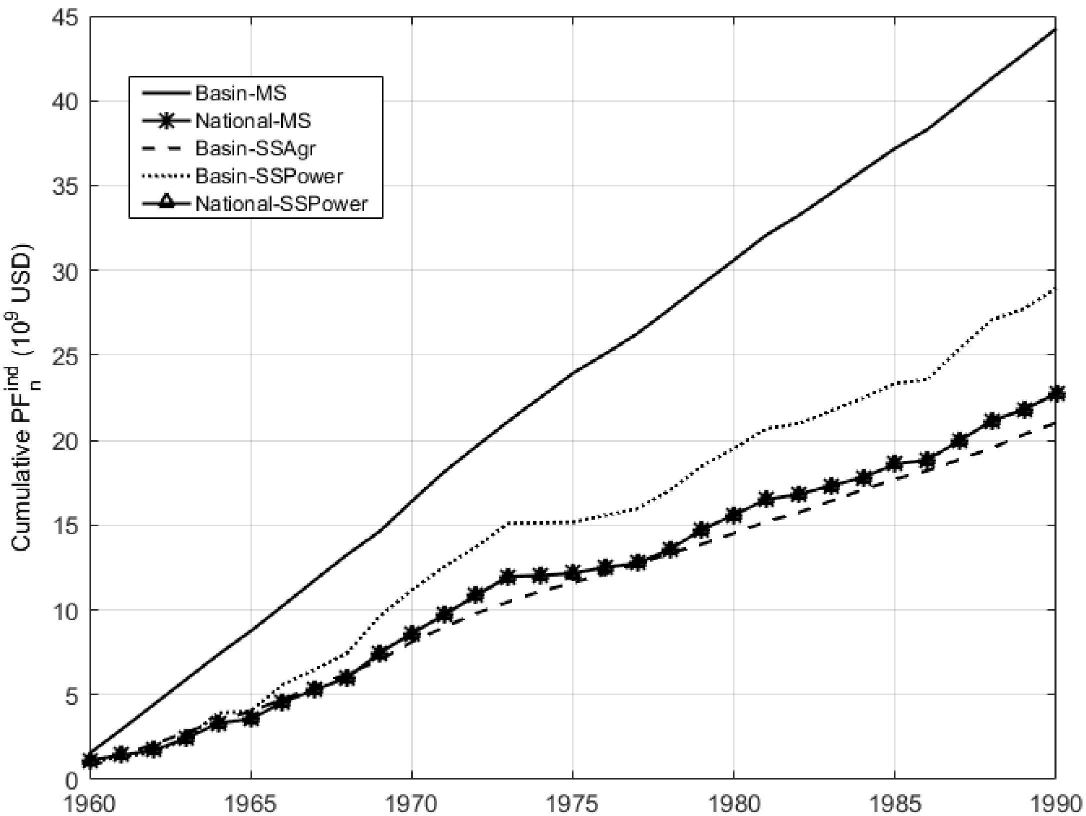

Fig. 7. Cumulative performance indicator.