Optimization of Syr Darya Water and Energy Uses

Elena Antipova, Hydropower Engineer,
Hydrotechnical Service, JSC Kyrgyzenergo, Bishek, Kyrgyz Republic

Alexi Zyryanov, Head,
Hydrotechnical Service, JSC Kyrgyzenergo, Bishek, Kyrgyz Republic

Daene McKinney*, Associate Professor,
Environmental and Water Resources Engineering Program
The University of Texas at Austin, USA

and

Andre Savitsky, Hydrologist,
Ecological Center, Tashkent, Uzbekistan

ABSRACT

Since independence, joint use of water resources in the Aral Sea basin has been a critical international problem between the Central Asian republics, especially in the Syr Darya basin where the tradeoffs between use of water for agricultural and energy production are very acute. Previous centralized methods of planning, formation of independent countries and the emergence of national interests have made the coordinated operation the Naryn-Syr Darya Cascade of reservoirs complicated. In order to implement recent international agreements on the use of water and energy resources of the Syr Darya basin providing for the mutual supply of electric fuel and energy resources to settle water and energy relations, a model was developed to optimize operation modes for the major reservoirs of the basin. This model was used as the basis for developing a complex model of the operation of the Naryn Cascade of hydropower plants and the interactions of the Kyrgyz Republic energy system and the other Syr Darya basin countries through the Central Asian electricity pool. The model is described and the results of using the model to analyze three scenarios of Nayrn Cascade operation are presented.

INTRODUCTION

Joint use of water resources in the Aral Sea basin is one of key international problems between the Central Asian countries of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. This problem is especially acute in the Syr Darya basin (see Figure 1), where flow regulation amounts to 93 %, and all water resources are utilized. The major water consumer in the basin is irrigated agriculture, and major water users include hydroelectric power plants (HPPs). Previously, within the USSR, regulation of water use for irrigation and electric power generation was centralized; formation of independent countries in Central Asia made these issues

---

* Corresponding Author. Daene C. McKinney, Center for Research in Water Resources, PRC 119, University of Texas, Austin Texas, 78712, (phone: 512-471-8772; fax: 512-471-0072; email: Daene@aol.com).

more complicated. National interests joined the already arisen regional crisis of the Aral Sea. Consequently, these problems have disrupted the coordinated operation the Naryn-Syr Darya Cascade of reservoirs from the previous single schedule and orientation primarily for water supply to irrigated areas of the basin.

Under these circumstances, the need for a new agreement on a high level became apparent. Such an agreement was developed under the aegis of the Executive Committee (EC) of the Central Asian Economic Community (CAEC). On March 17, 1998, Prime Ministers of the Republic of Kazakhstan, the Kyrgyz Republic, and the Republic of Uzbekistan signed the agreement on the use of water and energy resources of the Syr Darya basin between governments of these countries. Later (in 1999), the Republic of Tajikistan joined this agreement.

This agreement provides for mutual supplies of electric power, fuel and energy resources to settle water and energy relations between the basin countries. The agreement also defines areas of future joint activities concerning rational use of water, fuel and energy resources in the region. Concurrent with the Syr Darya agreement, the countries signed an agreement on the parallel operation of the energy systems of Central Asia, the agreement on cooperation in the area of environment and rational nature use, and other interstate acts. These agreements complement each other and open up opportunities for closer cooperation.

It became apparent that the Syr Darya water and energy agreement, being a framework agreement, required implementation mechanisms. Meetings of the Water and Energy Uses Round Table under the EC CAEC address these issues. At these meetings heads of water and energy sectors and representatives of governmental agencies of the countries participating in the agreement take part. In past meetings, participants noted the importance of developing a model to optimize operation modes for the major reservoirs of the Syr Darya basin that form the Naryn-Syr Darya Cascade. The Round Table (with financial and technical assistance from USAID) initiated development of a model to optimize operation modes of major reservoirs of the Naryn-Syr Darya Cascade with the help of a group of specialists from the water and energy sectors of their countries and organizations. Three component models (river, energy and planning zone) were prepared in the General Algebraic Modeling System (GAMS) programming language (*Brooke et al.,* 1998) as stand-alone components.

To achieve tighter integration of the water and energy model components the river component was used as a base for developing a complex energy model for the Naryn Cascade of HPPs, including the interactions of the Kyrgyz Republic and the other Syr Darya basin countries through water supplies and mutual fuel (energy carrier) deliveries. Since their independence the five Central Asian republics (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) have been striving to find ways of allocating and sharing the integrated water and energy systems developed under the Soviet Union. In this region, it is necessary to balance the solution of these resource management problems across several nations and several river basins. The work reported here is the first phase of a larger work involving the solution of the water and energy resources use problem for both the Syr Darya and Amu Darya river basins and the combined energy systems of all five Central Asian countries.

WATER AND ENERGY FACILITIES OF THE SYR DARYA BASIN

Construction of Toktogul reservoir in the Syr Darya basin was called for by the agricultural production targets set by the government of the former Soviet Union. These targets were aimed at quickly raising cotton production in the country from 4.3 million tons in 1960 to 10-11 million tons in 1990. In implementing these targets, great importance was placed on developing irrigation in the Syr Darya basin, the most important cotton farming region in Central Asia. It was anticipated that irrigated lands would be increased in the Syr-Darya basin from 2.1 million hectares in 1960 to 6.4 million hectares by 1990. However, as early as 1960 the total water diversion in the basin amounted to over 30 km^3, exceeding the actual flow of the river in low water years. At that time the capacity of the water infrastructure of the basin could not meet the demand for irrigation water in dry periods. At midstream, the Kairakum reservoir depended on the natural river flow, since there were no multi-year storage reservoirs in the basin. At that time, there were three main flow control systems in the Syr Darya basin: Kairakum reservoir (2.6 km^3 active storage capacity), and Farkhad and Kyzylorda Hydraulic Systems. Construction of the Chardara reservoir (4.7 km^3 active storage) was near completion. More intensive was the construction of canals: the Big Fergana Canal, the North-Fergana Canal, secondary canals and other facilities.

Because of poor coordination of the areas under development and low efficiency of the irrigation systems, the discrepancy between irrigation demand and water supply in almost all watercourses in the basin was very acute. In order to improve available water supply, construction of Charvak reservoir (1.2 km^3 active capacity) started on the Chirchik river and the Kampuravatsky reservoir (1.6 km^3 active capacity) on the Karadarya river. However, seasonal flow control of the Syr Darya river and its tributaries did not solve the problem of stable water supply because of significant discrepancies between anticipated and actual levels in low water years. Because of this, it was decided to implement multi-year storage by construction of Toktogul reservoir (14 km^3 active capacity and 8.7 km^3 firm yield) on the Naryn river with an operating regime determined by irrigation requirements. With the reservoir in place, the firm water resources in the middle and lower reaches of the Syr Darya river increased by 4.5 km^3 - more than by 30%.

The use of the reservoir for power generation was considered a side benefit. Since the impact of Toktogul reservoir on irrigation is limited to the Syr Darya basin and power generation affects the whole Central Asian region, a hydroelectric power plant (HPP) was constructed at Toktogul. Construction of the Toktogul HPP and 500 kV high-voltage lines closed the main loop of the Central Asian Energy Pool (CAEP) and increased the reliability and quality of power supply to users in the region.

The initial design of Toktogul reservoir specified that, in accord with the irrigation regime, the release from the reservoir in the non-vegetation season (October – March) should be limited to 180 m^3/sec, providing for minimum electricity generation. The irrigation release regime is very close to the natural one, enabling not only the preservation of the environment but also the creation of conditions for maintaining the required land reclamation conditions in the areas adjacent to the river.

Toktogul reservoir was commissioned in 1974, and for a long time it could not be filled to capacity. Its storage did not exceed 5-6 km^3 and only with the beginning of high water years in August 1988 did the reservoir storage finally reach full capacity (19.5 km^3). By 1990, the system was managed according to the design requirements. By that time, irrigated areas in the Syr Darya basin had reached 3.30 million hectares.

WATER AND ENERGY COMPLEXES IN THE SYR DARYA BASIN

Energy complex of Kyrgyzstan and the Naryn river

The Kyrgyz energy system comprises 17 operating power plants with the total capacity of 3,586 MW including 15 HPPs (2,948 MW) and 2 thermal electric power plants (TPP) (638 MW). In the areas of the republic within the Syr Darya basin, there are 5 big HPPs (Toktogul, Kurpsai, Tashkumyr, Shamaldysai and Uch-Kurgan) located in a cascade in the lower reaches of the Naryn river. The total rated capacity of HPPs in the Naryn Cascade is 2,870 MW and average long-term output of electric power is 10,000 million kWh/year. Thermal power plants in Bishkek (588 MW) and Osh (50 MW) with total design output of 4,100 million kWh/year are run on natural gas, fuel oil and coal (Bishkek TPP). HPPs account for 82% of the rated capacity and more than 90% of the electric power generation. However in the HPP balance over 97% of the capacity is concentrated in the Naryn Cascade controlled by Toktogul Reservoir. Other HPPs of the cascade have small storage capacity and provide daily control of discharges from upstream. Basic characteristics and parameters of the Naryn Cascade are given in Table 1.

National and regional interests of the Syr Darya riparian nations in the use of water and energy resources of the basin

Before 1990, most of the power generated by the Naryn Cascade HPPs from vegetation period (April-September) releases was transmitted to neighboring regions. Kyrgyzstan in the non-vegetation period (October - March) received electric power from the CAEP, and natural gas, coal and fuel oil for TPPs from the other regions (now the independent Central Asian republics and Russia). Fuel consumption and electric power production by TPPs are summarized in Table 2. The scheme existing at that time ensured efficient and integrated operation of the fuel-and-power sectors and water complexes of the region (see Figure 2, irrigation mode).

The situation changed drastically in 1991, when independent states were established in Central Asia. Because of complications in intergovernmental relations and account settlements, introduction of national currencies, growing prices of oil, coal, natural gas and transportation, the supply of fuel and electricity to Kyrgyzstan from the other republics was reduced. This radically affected the structure of the Kyrgyz fuel-and-energy balance. Because of decreased production of fuel in Kyrgyzstan, the output and distribution of thermal power from TPPs fell two times and organic fuel consumption reduced, giving rise to increased electric power demand by the population for heating, hot water supply and cooking. With these changes, the Kyrgyz electricity demand in the non-vegetation period increased from 50% of the annual amount in 1990-91 to 75% in 1996-99 (see Figure 2).

To provide for the electric power demand in Kyrgyzstan under these conditions, the Toktogul operation mode was switched from irrigation to power generation. Toktogul HPP is the main power plant in the Naryn Cascade providing average long-term generation of electricity of 5,000 million kWh (45% of the Kyrgyz energy balance). The share of hydropower in republic's electricity balance did not exceed 70% prior to 1990. However, in subsequent years it rose to 91% and Toktogul releases for power generation in non-vegetation periods rose from 2.8 km^3 to 8.5 km^3 (see Figure 4). Intensive use of water resources for power generation, along with changes in the Toktogul operating regime created serious problems in the Syr Darya basin in both summer and winter periods. The years 1991-94 and 1999 were typical of deviations from the earlier pattern of Naryn river water management. In that period, the supply of electricity and fuel to Kyrgyzstan in the non-vegetation period from Kazakhstan and Uzbekistan fell more than two times compared to 1990. In addition, the downstream reservoirs were not able to store the increased releases, and, in order to prevent flooding of the lower reaches of the Syr Darya river, wasteful discharges into the Arnasai depression were required. As early as the vegetation period of 1994, discharges to Arnasai exceeded 8.0 km^3, increasing its storage up to 25 km^3.

Intergovernmental relations of joint water and energy use in the Syr Darya basin

Starting in 1995, in order to overcome increasing difficulties, a number of intergovernmental agreements were signed by Kazakhstan, Kyrgyzstan and Uzbekistan related to the use of water and energy resources in the Syr Darya basin. These agreements specified releases from Toktogul reservoir during vegetation periods to meet basin irrigation demands and non-vegetation period compensative supplies of energy resources (natural gas, electric power, fuel oil and coal) from Uzbekistan and Kazakhstan to Kyrgyzstan for extra HPP generated electricity transmitted to those republics due to summer water releases (Figs. 2 and 3).

Every year, proposals for the mutual supply of water and energy resources are elaborated by working groups from the participating republics at the level of top-management of concerned sectors of the water, fuel, and power industries, and the regional energy and water management bodies (UDC "Energia" and BVO "Syr Darya"). After that, the proposals are ratified in intergovernmental agreements. During 1995-98, bi-lateral agreements between Kyrgyzstan and Uzbekistan were signed specifying vegetation period water releases from Toktogul reservoir (typically 6.5 km^3)[1] for irrigation purposes in Uzbekistan and Kazakhstan and electric power transfers (typically, 1.1 billion kWh each to Uzbekistan and Kazakhstan)[2]. Mutual supplies of electric power and coal from Kazakhstan were to be delivered to the Bishkek TPP and electric power, natural gas and heating oil from Uzbekistan were to be delivered. To achieve joint solutions over the near term, heads of the Kazakhstan, Kyrgyzstan and Uzbekistan governments signed a long-term framework agreement "On the Use of Water and Energy Resources of the Syr Darya Basin" on 17 March 1998. Later (1999) the Republic of Tajikistan joined this agreement.

---

[1] The release (6.5 km3) has theoretically been split equally between Uzbekistan and Kazakhstan, but Uzbekistan has first access to the water and Kazakhstan receives high salinity water and sometimes reduced flows.

[2] The 2.2 billion kWh of electricity received by Kazakhstan and Uzbekistan is the residual energy remaining from that generated from the 6.5 km3 vegetation period release after Kyrgyz national electric demand is satisfied.

Under the agreements, Kyrgyzstan transmitted to Uzbekistan and Kazakhstan during 1995-99, 7,200 million kWh of surplus electricity due to Toktogul vegetation period releases. During the same period, Kazakhstan and Uzbekistan supplied to the Kyrgyz energy system: 1,500 million kWh electricity, 1.73 km^3 natural gas, 2.17 million tons of coal and fuel oil for the Bishkek TPP autumn-winter operation. Unfortunately, partial alteration of the Toktogul irrigation mode did not solve the problem on the whole. Year-to-year, seasonal redistribution of water for power and irrigation without a comprehensive approach lead to a reduction in Toktogul storage to 7.2 km^3 (dead storage = 5.5 km^3) by the beginning of the 1998 vegetation period (see Figure 4).

During 1998 and 1999, the terms of the intergovernmental agreements were only partially fulfilled. Favorable hydrologic and weather conditions contributed to reduced vegetation period water demand (Toktogul releases in 1998 = 3.7 km^3, and in 1999 = 5.06 km^3). Due to this, Kyrgyzstan supplied less electric power to Uzbekistan and Kazakhstan than planned; however, Uzbekistan fulfilled its obligations for natural gas supply. Table 3 summarizes the water releases and the energy resource supplies stipulated by the agreements and actually delivered for the period 1995-99. By receiving energy resources as compensation for seasonal control of flow through Toktogul reservoir, Kyrgyzstan not only reduces long-term control capability, but sometimes is forced to discharge the long-term stock of the reservoir, thus decreasing the efficiency of flow use and electricity generation at the Naryn Cascade HPPs. Though Kazakhstan and Uzbekistan have been providing some compensation to Kyrgyzstan for extra energy and control of water, these republics, without respective compensation, will not have guarantees of firm water supply on a long-term basis.

In 1999 the governments ratified documents stipulating synchronous or parallel operation of the national energy systems of all Central-Asian republics. These existing agreements (water and energy, and parallel operation) provide a base for stable regional cooperation in balanced usage of water and fuel-energy resources. That base provides:

- Implementation of coordinated water and energy policy of the republics aimed at joint development and operation of fuel-energy and water resource systems;
- Elaboration of a cooperative program of new structural and regional policy in the development of the water and fuel-energy sectors;
- Setting up a common market of energy resources;
- Elaboration of regulatory legal documents and setting up intergovernmental, market-type structures; and
- Attraction of investments of private and national capital both from Central Asian republics and other countries.

However, practical implementation of the long-term mechanism of water and energy use requires much additional joint work. This joint work has to be carried out in the engineering, legal and organizational directions for the purpose of bridging the gap between national legislative acts guiding the relationships of the participants with different forms of ownership.

Due to the fact that the existing pattern of relationships in the water and power sector does not meet the interests of any of the riparian nations of the Syr Darya basin and is not optimal for the region as a whole, the Water and Energy Uses Round Table noted the importance of developing a model to optimize operation modes for the major reservoirs of the Syr Darya basin. The resulting system is a complex of models to assist in solving the tasks of optimal flow control with regard to national and regional benefits and with subsequent agreement on the regimes at the intergovernmental level in order to enter into bilateral and multilateral long-term economic agreements (*McKinney and Kenshimov,* 2000). In the course of this work, a complex energy model was developed for the Naryn Cascade of HPPs, including the interactions of the Kyrgyz Republic and the other Syr Darya basin countries through water supplies and mutual fuel (energy carrier) deliveries.

OPTIMIZATION MODEL OF THE NARYN CASCADE

Problem definition and general requirements of the model

The water and energy model described here has been developed using the General Algebraic Modeling System (GAMS) (*Brooke et al*., 1998; *McKinney and Savitsky*, 2001) for the purpose of solving water and energy problems of the Kyrgyz energy system taking into account national benefits and regional water requirements. The model includes two parts: a water part and an energy part. The water part is based on the model of the BVO "Syr Darya" (*McKinney and Kenshimov*, 2000) and incorporates reservoirs, HPPs, sources, national water users, and water delivery to downstream users. With the help of this program, taking into account the initial data and constraints, flow rates through the HPPs, balances of reservoirs, and water supply to Kyrgyz and downstream users and the output of HPPS are calculated. The energy part of the model calculates the most efficient load on the generating plants (both thermal and hydro) satisfying Kyrgyz internal energy demand and regional electricity transfers through the CAEP. An economic factor in these calculations is the cost of energy produced and the tariffs for electricity transfers to and from the regional grid. The water and energy parts are interconnected via the output of HPPs. Since the plants of the Naryn Cascade are located on one and the same water course, they are presented in the energy part as a single plant with the total output of all plants of the cascade.

Initial data

The model has been developed for the Kyrgyz energy system. Diagrams of the water and energy parts of the model are shown in Figure 5. The water part includes the following:

- Five water reservoirs of the Naryn Cascade: Toktogul, Kurpsai, Tashkumyr, Shamaldysai, and Uch-Kurgan;
- Three water sources: inflow to Toktogul reservoir, lateral inflows to both Kurpsai and Tashkumyr reservoirs;
- Two Kyrgyz water users: water diversions from Uch-Kurgan reservoir to the Left Bank Canal (LBC) and Big Namangan Canal (BNC); and
- River mouth - Transmission of water to downstream water users from the Uch-Kurgan HPP: Uzbekistan, Tajikistan, Kazakhstan, and the Aral Sea.

The energy part of the model includes the following:

- Generating plants (HPP and TPP) whose loads are calculated by the model taking into account costs and imposed constraints;
- Off-design plants whose loads are specified and remain unchanged in all calculations;
- A single energy consumer, the internal demand of the Kyrgyz Republic; and
- Regional energy transfer to and from the CAEP.

The entities and initial information included in the model are listed in Tables 4-9.

Optimization criteria

The optimization criterion in this model is to minimize the cost of providing the Kyrgyz Republic's internal energy demand while taking into account Toktogul reservoir operation in the electricity generation or irrigation modes. This criterion is embodied in the objective function as minimization of electricity production costs for thermal and hydroelectric plants and the squared differences between modeled energy delivery and demand

$$\mathit{Minimize}\ \sum_{t}\left[C_H EH_t + C_G EG_t + C_O EO_t + \left(E_{Kyrgyz,t} - ED_{Kyrgyz,t}\right)^2\right]$$

where

C_H	electricity production cost for TPP ($/million kWh);
C_G	electricity production cost for Naryn Cascade HPP ($/million kWh);
C_O	cost for electricity transfer to/from CAEP ($/million kWh);
EH_t	electricity production of TPP in period *t* (million kWh);
EG_t	electricity production of Naryn Cascade HPP in period *t* (million kWh);
EO_t	electricity transfer to/from CAEP in period *t* (million kWh);
$E_{Kyrgyz,t}$	energy produced for Kyrgyz Republic in period *t* (million kWh); and
$ED_{Kyrgyz,t}$	Kyrgyz Republic's internal energy demand in period *t* (million kWh)

For water users, the optimization criterion is similar to that in the BVO "Syr Darya" model (*McKinney and Kenshimov*, 2000). The main criterion is to minimize deficits of water delivery to all users

$$\mathit{Minimize}\ \sum_{t}\sum_{j=1}^{3}\frac{W_{req,j,t} - W_{in,j,t}}{W_{req,j,t}}$$

where

$W_{req,j,t}$	demand for LBC (*j* = 1), BNC (*j* = 2), and downstream users (*j* = 3) (m^3); and
$W_{in,j,t}$	delivery to LBC (*j* = 1), BNC (*j* = 2), and downstream users (*j* = 3) (m^3).

Constraints

The water part of the model is a sequential arrangement of the five reservoirs and HPPs of the Naryn cascade with lateral inflows and water diversions. For every reservoir, water storage balances are observed as follows:

$$V_{j,t} - V_{j,t-1} = \sum_{in} W_{in,j,t} - W_{out,j,t}$$

where

$V_{j,t}$	volume of water in reservoir *j* at time *t* (m^3);
$W_{out,j,t}$	release from reservoir *j* in period *t* (m^3); and
$W_{in,j,t}$	inflow to reservoir *i* in period *t* (m^3);

The generation of each HPP of the Naryn Cascade is calculated according to the following equation:

$$P_{j,t} = \gamma * \varepsilon_j * Q_{j,t} * \Delta H_{j,t}$$

where

$P_{j,t}$	power generated by HPP *j* in period time *t* (kW);
$Q_{j,t}$	flow through HPP *j* in period time *t* (m^3/sec);
$\Delta H_{j,t}$	effective head on HPP *j* in period time *t* (m); and
ε_j	efficiency of HPP *j*

The output of electric energy at HPPs for the design period is calculated according the following equation:

$$E_{j,t} = \Delta t / 3600 * P_{j,t}$$

where

$E_{j,t}$	energy generated by HPP *j* in period time *t* (million kWh)
Δt	number of seconds in the period *t*

All entities of the energy part of the model are connected by one equation: the total output of all generating plants is equal to the internal consumption and balance of transfers to/from the CAEP

$$\sum_t \left[EH_t + EG_t + ESG_t \right] = \sum_t \left(E_{Kyrgyz,t} + EO_t \right)$$

where ESG_t is the power output of the non-calculated power stations. The relationship of the water part and the energy part of the model is

$$\sum_{j \in G} E_{j,t} = EG_t$$

In order to provide for compulsory minimum loading of the Kyrgyz TPPs (according to the heating schedule), constraints on the electric power output of Kyrgyz plants are introduced. These constraints can be changed depending on the availability of fuel (coal and gas) in the Kyrgyz Republic.

RESULTS

Model verification

To verify the reliability of the model, the 1998-99 operation mode of Toktogul reservoir was modeled. The initial information used was the actual energy balance of Kyrgyzenergo from October 1998 to October 1999, as well as actual water levels of reservoirs and reservoir inflow. The results gave the operation mode of the reservoirs and electric power output for each Naryn Cascade HPP. The difference between the modeled and actual volumes of water released from Toktogul was 270 million m^3, or 2.9% of the actual value. In addition, analysis of the output of each HPP was performed. The results suggest that on the Shamaldysai - Uch-Kurgan section there are unaccounted for water losses because the modeled output exceeds the actual. The other reaches show an opposite trend - this imbalance may be connected with inaccurate estimation of lateral inflows on these reaches. For additional details on the verification of the model see *Zyryanov and Antipova* (2000).

Three scenarios of operation of the Naryn Cascade

Three operation scenarios of the Naryn Cascade HPPs and the energy system of Kyrgyzstan were modeled. Table 8 shows the results of modeling each scenario. Toktogul reservoir storage volumes are shown in Figure 6 for all three scenarios.

Scenario 1 considers the problem of electric power supply to internal consumers of Kyrgyzstan with no electricity transfer through the CAEP. The results show that the electric power output of the Kyrgyz TPPs was 847 million kWh, complying with the heating schedule. The output of the Naryn Cascade HPPs was 10,500 million kWh and the annual release of water through the hydropower units of the Toktogul HPP was 11.6 km^3, exceeding the annual long-term inflow of Toktogul reservoir.

Scenario 2 envisages operation of Toktogul reservoir according to the irrigation regime in the vegetation period. This scenario models the intergovernmental agreements of 1995-99. In this case additional constraints were introduced:

- Minimum volume of water released through the Toktogul HPP in the vegetation period (6.5 km^3); and
- On electricity transfers to/from the CAEP:
    - ➢ No electric power transfer in the non-vegetation period; and

- Positive electric power transfers in the vegetation period to allow for electric power output above the Kyrgyz internal demand due to irrigation water releases.

The results show that surplus electric power of 2,710 million kWh was generated (See Table 8). In this case Toktogul operates as a seasonal regulator of releases for irrigation in the Syr Darya basin of 6.5 km^3. In the non-vegetation period, (since no fuel deliveries from downstream countries are assumed) to provide for Kyrgyz internal electrical consumption, release of 9.0 km^3 water is required through the Toktogul HPP. The annual output of the Naryn Cascade HPP was 13,000 million kWh and of the TPPs – 1,050 million kWh.

According to Scenarios 1 and 2, thermal power generation remains at a minimum level equal to 1,875 thousand Gcal in the non-vegetation period. Therefore, the Kyrgyz internal electrical demand, according to these scenarios, is much higher because the population must use electric resistance heating appliances. This requires raising the output of the Naryn Cascade HPPs and, increasing releases from Toktogul. This result (annual water release from Toktogul of 15.5 km^3 along with the annual long-term inflow of 11.2 km^3) would cause severe drawdown of the Toktogul reservoir and therefore rather serious problems both in the energy sector of Kyrgyzstan and in the whole integrated water system of the Syr Darya basin.

Scenario 3 considers the problem of long-term control of the Naryn river. The only constraints are on the annual release of water from Toktogul equal to the annual long-term inflow of the Naryn river to the Toktogul Hydrosystem. The results show that TPP electric power output is 2,400 million kWh with maximum generation in the non-vegetation period, resulting in minimal Kyrgyz hydropower demand in this period. The output of the Naryn Cascade HPPs is 10,500 million kWh, and electricity import from the CAEP in the non-vegetation period is 2,100 million kWh. Electricity export to the CAEP in the vegetation period is 3,700 million kWh, and the annual release from Toktogul is 11.2 km^3 including 7.4 km^3 in the vegetation period. Finally, to meet the Kyrgyz heating demand of 2.6 thousand Gcal, the gross annual output of the Kyrgyz TPPs is 6,600 million kWh.

CONCLUSIONS

The recent experience of cooperation in the use of the Syr Darya basin water and energy resources on the basis of intergovernmental agreements has been seasonal. It considers primarily the benefits of energy resource exchanges and does not solve the task of long-term, balanced use of water. This can cause, as was seen recently, the early depletion of Toktogul reservoir storage and huge losses both in the power and water sectors of the Central Asian republics. A situation similar to the depletion of all active storage in Toktogul reservoir arose in the beginning of the vegetation period of 1998, following the low-water year of 1997.

Apart from this, in the non-vegetation periods of 1999-2000 and 2000-2001 the supply of natural gas to Kyrgyz TPPs was terminated by Uzbekistan. As a result, because of extra loading of the Naryn Cascade HPPs, the release of water from Toktogul was increased substantially in those periods compared to the same period of earlier years. Much of the additional discharge of water was required to be thrown into the Arnasai depression from the Chardara reservoir and this aggravated the ecological situation in the lower reaches of the basin. These factors confirm the necessity of the parties fulfilling the annual intergovernmental obligations and the need for multi-year operation procedures for long-term control and use of water from Toktogul.

Within the framework of the model presented here, calculations of operating Toktogul with different sets of initial parameters have been performed. The results confirm that it is possible to change the regime of releases from Toktogul provided that the parties increase compensating supplies of energy resources. The results of the model can be used by the parties for further work on interrelations of all basin components and elaboration of a model of long-term control and usage of water and energy resources in the Syr Darya basin. This model has been fully integrated into the previously developed "BVO Syr Darya" model and can be solved for the detailed water delivery in the basin as well as consideration of salt concentrations in the river. Further, the concept implemented in the model reported has been extended to a comprehensive model of water and energy use in the Aral Sea basin, including both the Syr Darya and Amu Darya river basins and the energy systems of all five Central Asian republics (see Figure 10).

ACKNOWLEDGEMENTS

Financial support for this work was provided by the United States Agency for International Development (USAID) under contract Contract No. PCE-I-00-96-00002-00, Task Order No. 813, Environmental Policies and Institutions for Central Asia. The opinions expressed here are those of the authors and imply no position or opinion of the US government or USAID.

REFERENCES

Brooke A., D. Kendrick, and A. Meeraus. 1998, *GAMS: A User's Guide*, GAMS Development Corporation, Washington, DC.

McKinney, D.C. and A.K. Kenshimov (eds.), *Optimization of the Use of Water and Energy Resources in the Syr Darya Basin Under Current Conditions*, *Technical Report 00-06-W*, Environmental Policies and Institutions for Central Asia (EPIC) Program, US Agency for International Development, Almaty, Kazakhstan, 2000. [http://www.ce.utexas.edu/prof/mckinney/papers/aral/00-06-W/EPIC-00-06-W.htm].

McKinney, D.C. and A.G. Savitsky, GAMS Tutorial for Water and Energy Management, *Technical Report 99-13-W*, Environmental Policies and Institutions for Central Asia (EPIC) Program, US Agency for International Development, Almaty, Kazakhstan, 1999 (revised 2001).

Zyryanov, A. and E. Antipova, "Optimization of the Syr Darya Water and Energy Uses under Current Conditions,", in McKinney, D.C. and A.K. Kenshimov (eds.), *Optimization of the Use of Water and Energy Resources in the Syr Darya Basin Under Current Conditions*, *Technical Report 00-06-W*, Vol. 2, Section 2.1, Environmental Policies and Institutions for Central Asia (EPIC) Program, US Agency for International Development, Almaty, Kazakhstan, 2000.

ABOUT THE AUTHORS

Alexi Zyryanov is Head of the Hydrotechnical Service of the Joint Stock Company Kyrgyzenergo in Bishek, Kyrgyz Republic.

Daene McKinney is an Associate Professor in the Environmental and Water Resources Engineering Program at The University of Texas at Austin. From 1998-2000, he was the Team Leader of the US Agency for International Development Environmental Policies and Institutions for Central Asia (EPIC) Program.

Elena Antipova is a Hydropower Engineer in the Hydrotechnical Service of JSC Kyrgyzenergo.

Andre Savitsky is a Hydrologist associated with the Ecological Center in Tashkent, Uzbekistan.

Table 1. Basic Parameters of the Naryn Cascade.

Item	Units	Naryn Cascade HPPs				
		Toktogul	**Kurpsai**	**Tashkumyr**	**Shamaldysai**	**Uch-Kurgan**
Rated capacity	MW	1,200	800	450	240	180
Annual long-term output of electric power	million kWh	4,100	2,630	1,555	902	820
Average long-term flow	m^3/sec	359	391	439	438	429
Typical reservoir levels						
a. Full storage (DFSL)	M	900	724	628	572	539.5
b. Dead storage (DSL)	M	837	721.6	626.5	569.9	536.5
Typical heads						
a. Maximum	M	180	106	58.5	31	36
b. Minimum	M	110	90.5	40	25.2	18.5
c. Estimated	M	140	91.5	53	26	29
Reservoir area at DFSL	km^2	284.3	12.0	7.8	2.4	4.0
Storage at DFSL	million m^3	19,500	370	140	39.4	52.5
Active storage capacity	-	14,000	35	10	5.42	20.9
Type of control		Long-period	Weekly	Weekly	Weekly	Daily
Number of turbines	Pcs	4	4	3	3	4
Design flow rate per turbine	m^3/sec.	250	243	319	345	190
Max. flow rate through turbines	-	960	972	957	1,035	760
Hydropower unit efficiency	%	87	90	85	80	80
Unit flow rate of water per 1 kWh at $H_{estimated}$	m^3/kWh	2.95	4.4	7.7	15.6	14.0
Flow rate through water passage structures at DFSL, total:	m^3/sec	3,500	2,537	3,293	3,090	3,250
Bottom spillway	-	2,340	1,037	2,093	3,090	2,296
Transfer spillway	-	1160	1500	1200	-	954

Table 2. Fuel Consumption and Electric Power Production at Kyrgyz TPPs in 1988-99.

Fuel		Units	Year											
			1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Coal	Total	thous. tons	1,383.2	1,337.8	1,043.6	1,016.3	1082.2	948.5	776.2	770	460.2	503.6	366.5	340.4
	Kyrgyz	thous. tons	746.3	794.3	568.5	426.5	628.9	465.5	110.5	36.5	41.5	98.1	40.9	23.0
Fuel oil		thous. tons	380.7	420.2	373.5	317.0	136.5	125.9	85.1	45	5.4	37.1	31.6	36.9
Natural gas		million m^3	718.0	844.4	1,016.6	1,034.8	740.8	504.8	203.9	300	464.6	632.1	563.5	223.1
Electric power output		million kWh	4,108	4,287	4,202	3,914	2,603	2,090	1,140	1,169	1,428	1,656	1,631	981.7
Thermal power output		thous. Gcal.	5,145	5,668	5,688	5,806	5,153	4,311	3,013	2,957	3,195	2,795	2,716	2,054

Table 3. Implementation of Intergovernmental Agreements on the Use of Water and Energy Resources of the Syr Darya Basin in 1995-99.

Parameters	Year		1995		1996		1997		1998		1999	
	Units of measurement											
Toktogul	Storage											
1 January	bln.m^3		17.7		13.9		13.0		10.2		13.5	
1 April			14.2		10.4		9.8		7.3		10.4	
31 Dec.			15.6		15.2		11.8		15.1		14.5	
Veg. Period Release	bln.m^3	Plan	6.5		6.5		6.5		6.5		6,5	
		Actual	6.3		6.2		6.1		3.7		5.06	
Electric Power Export	million kWh	Plan	2200		2200		2200		2200		2200	
			Uzb	Kaz	Uzb	Kaz	Uzb	Kaz	Uzb	Kaz	Uzb	Kaz
		Actual	928	782	108	995	1615	710	489	469	970	585
Supply to Kyrgyzstan: Natural gas	million m^3	Plan	200	-	500	-	630	-	772	-	500	-
		Actual	200	-	476	-	632	-	748	-	331	-
Karaganda Coal	Thous tons	Plan	-	985	-	600	-	0	-	567	-	567
		Actual	-	450	-	202	-	0	-	150	-	572
Fuel oil	Thous tons	Plan	-	-	-	-	-	-	20		-	
		Actual	-	-	-	-	-	-	24			
Electric Power	million kWh	Plan	-	-	-	-	400	0	200	250	-	250
		Actual	-	-	-	-	434	11.4	75	150	-	-

Table 4. Initial Model Data.

Item (see Figures 4 and 5)	Initial Information
Inflows (*I*)	- Values of average long-period inflow for every time interval for every source.
Reservoirs (*V*)	- Curves of reservoir storage capacities as a function of water levels. - Constraints (maximum and minimum) on each reservoir storage. - Reservoir storage at the beginning of calculation. - For Toktogul reservoir, total water discharge for a given period of time (year or vegetation season) can be set.
HPP (*C*) in the water part of the model. HPP (*G*) in the energy part of the model	- Constraints on the flow rates through turbine units. - Downstream water elevation as a function of flow rate through HPPs. - Hydropower unit efficiencies with regard for losses in the penstock, turbine and generator. - Cost of electric power.
TPP (*H*)	- Constraints on output for a time interval (maximum and minimum). - Cost of electric power.
Small HPP (*X*)	- Average output of small HPPs for a time interval.
Electric power consumers (*A*)	- Internal demand of the Kyrgyz Republic for a time interval.
Export-import of electric power from CAEP (*O*)	- Transfers of electric power can be both set and estimated values. - Tariffs for electric power transfers.
Water users (*U*)	- Water demand for every time interval for every user.
River mouth (*R*)	- When solving the problems of water flow control, constraints on water releases can be set both for a given time interval, and a specified period (year, vegetation season).

Table 5. Average Long-term Inflows.

Item	Units	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.
Inflows													
Inflow to Toktogul reservoir	million m^3	557.1	471.7	380.3	372.3	331.4	420.5	596.2	1,446.3	2,255.0	2,249.9	1,392.8	777.6
Lateral inflow to Kurpsai reservoir	million m^3	26.8	23.3	21.4	30.8	28.8	32.1	33.2	64.3	88.1	133.9	93.7	33.7
Lateral inflow to Tashkumyr reservoir	million m^3	107.1	101.1	88.4	62.9	58.9	88.4	267.5	372.3	303.3	155.3	136.6	124.4
Water Demands													
Diversion to left-bank canal (LBC)	million m^3	13.4	13.0	13.4	13.4	12.1	13.4	38.9	40.2	38.9	40.2	40.2	38.9
Diversion to Big Namangan Canal (BNC)	million m^3	40.2	25.9	26.8	26.8	24.2	40.2	64.8	80.4	77.8	107.1	107.1	51.8
Energy Demands													
Internal Kyrgyz demand	million kWh	746	1,121	1,520	1,666	1,394	1,366	917	635	535	550	547	532

Table 6. Average Monthly Power Generation.

Item		units	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.
TPP	max	million kWh	345	345	345	345	345	345	100	45	45	45	45	45
	мin	million kWh	60	125	125	130	130	125	60	15	15	15	15	15
Small HPP	actual	million kWh	16	18	19	16	15	19	16	21	20	25	25	20
HPP	max	million kWh	2,135	2,066	2,135	2,135	1,929	2,135	2,066	2,135	2,066	2,135	2,135	2,066
	мin	million kWh	283	274	283	283	255	283	274	283	274	283	283	274

Table 7. Costs of Electric Power from Power Plants and Transfer from CAEP.

	Type of power plant				
	TPP	HPP	Small HPP	Transfer from CAEP	
Cost (tiin/kWh)	92	1.3	3.7	Rate (tiin/kWh)	100

Table 8. Results of Three Scenarios of Operation of the Naryn Cascade.

		Scenario 1			Scenario 2			Scenario 3		
Item	Units	Non-veg. period	Veg. period	Year	Non-veg. period	Veg. period	Year	Non-veg. period	Veg. period	Year
Consumption	mln kWh	7,813	3,716	11,529	7,813	3,716	11,529	7,813	3,716	11,529
Output of JSC KE:	mln kWh	7,813	3,716	11,529	7,813	6,424	14,237	5,710	7,422	13,132
Including: TPP	mln kWh	712	135	847	723	325	1,048	2,070	325	2,395
Small HPP	mln kWh	103	127	230	103	127	230	103	127	230
Naryn Cascade HPP	mln kWh	6,998	3,454	10,452	6,987	5,972	12,959	3,537	6,970	10,507
Transfers from CAEP "+" export	mln kWh					2,708	2,708		3,706	1,603
"-" import	mln kWh							-2,103		
Ave. long-term inflow to Toktogul	mln m^3	2,533	8,718	11,251	2,533	8,718	11,251	2,533	8,718	11,251
Releases from Toktogul Volume	mln m^3	8,178	3,396	11,574	9,000	6,500	15,500	3,768	7,432	11,200
Flow rate	m^3/sec.	520	215	367	572	411	492	240	470	355
Toktogul reservoir										
Elevation beginning of period	m	889	865	888.5	889	865.3	888.5	888.5	883.4	888.5
Storage at beginning of period	bln m^3	16.3	10.7	16.3	16.3	10.8	16.3	16.3	15.1	16.3
Elevation at end of period	m	865	886.8	886.8	865.3	875	875	883.4	888.2	888.2
Storage at end of period	bln m^3	10.7	16	16	10.8	13	13	15.1	16.4	16.4
"-"drawdown. "+"filling "	bln m^3			-0.3			-3.3			0.1

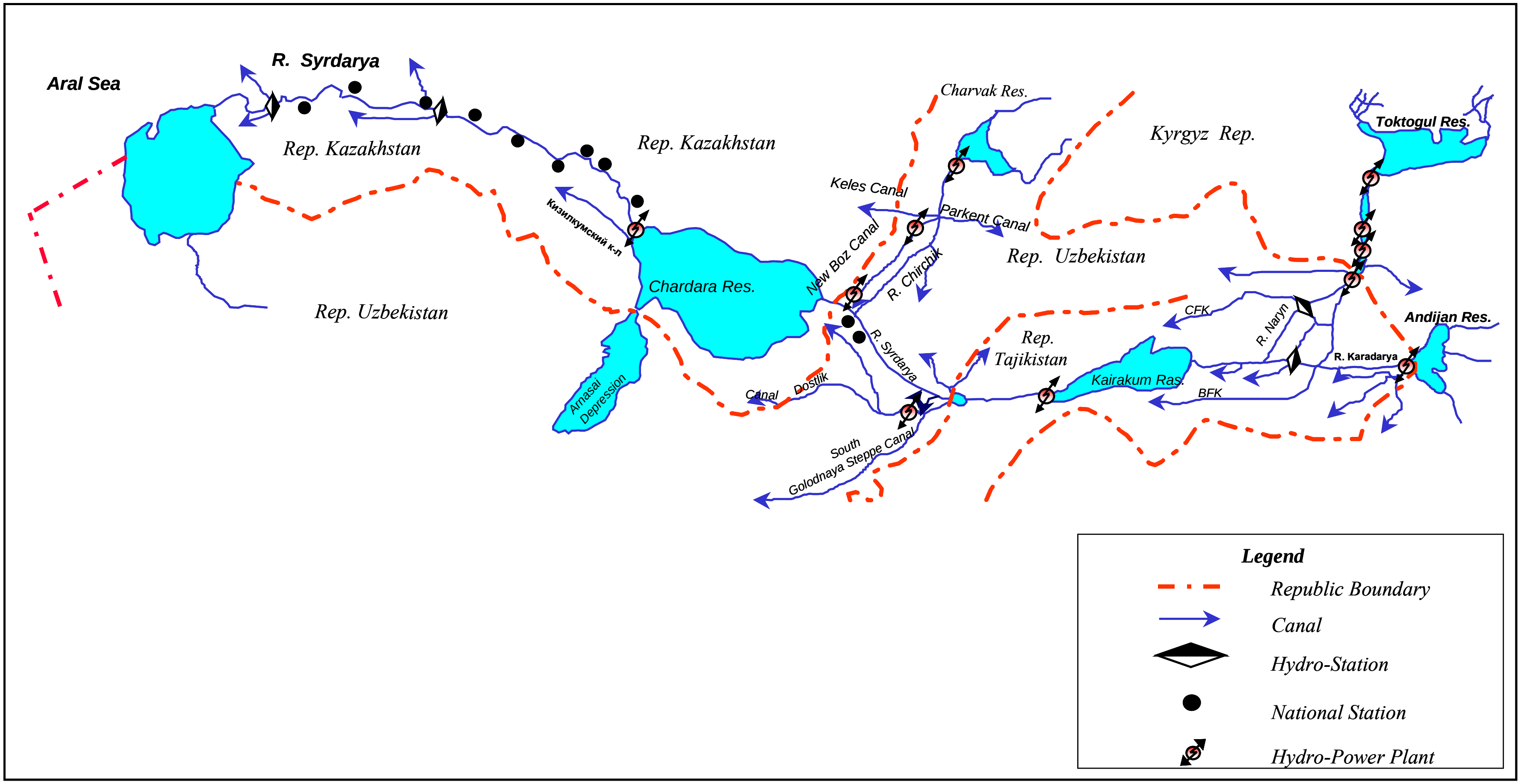


Figure 1. Scheme of the Syr Darya basin (Source: WARMAP Project).

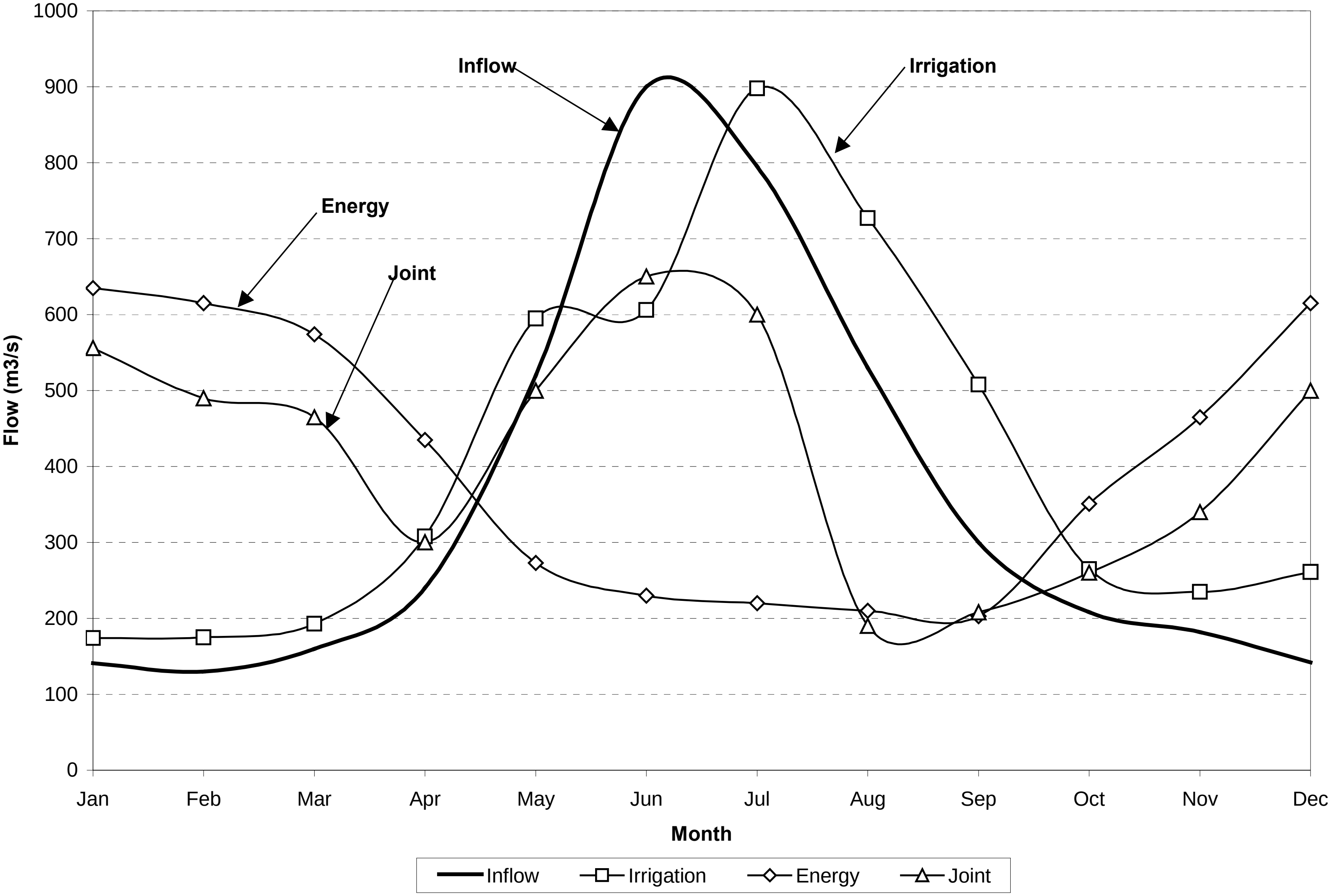


Figure 2. Toktogul reservoir operation under different regimes.

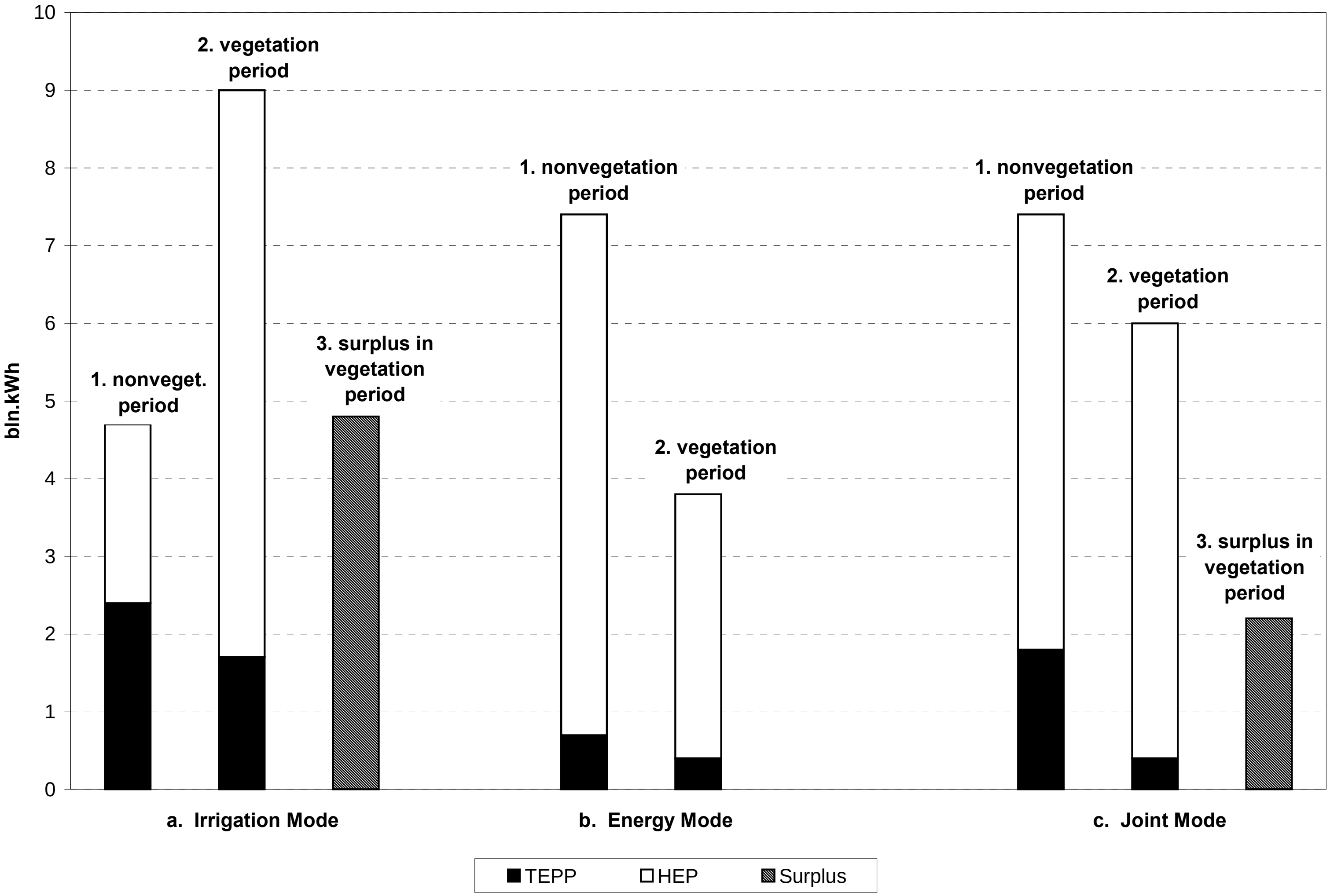


Figure 3. Kyrgyz electricity output under different Toktogul operation scenarios:
a – irrigation; b – energy; c – joint;
1 – non-vegetation period; 2 – vegetation period; 3 – surplus in vegetation period.

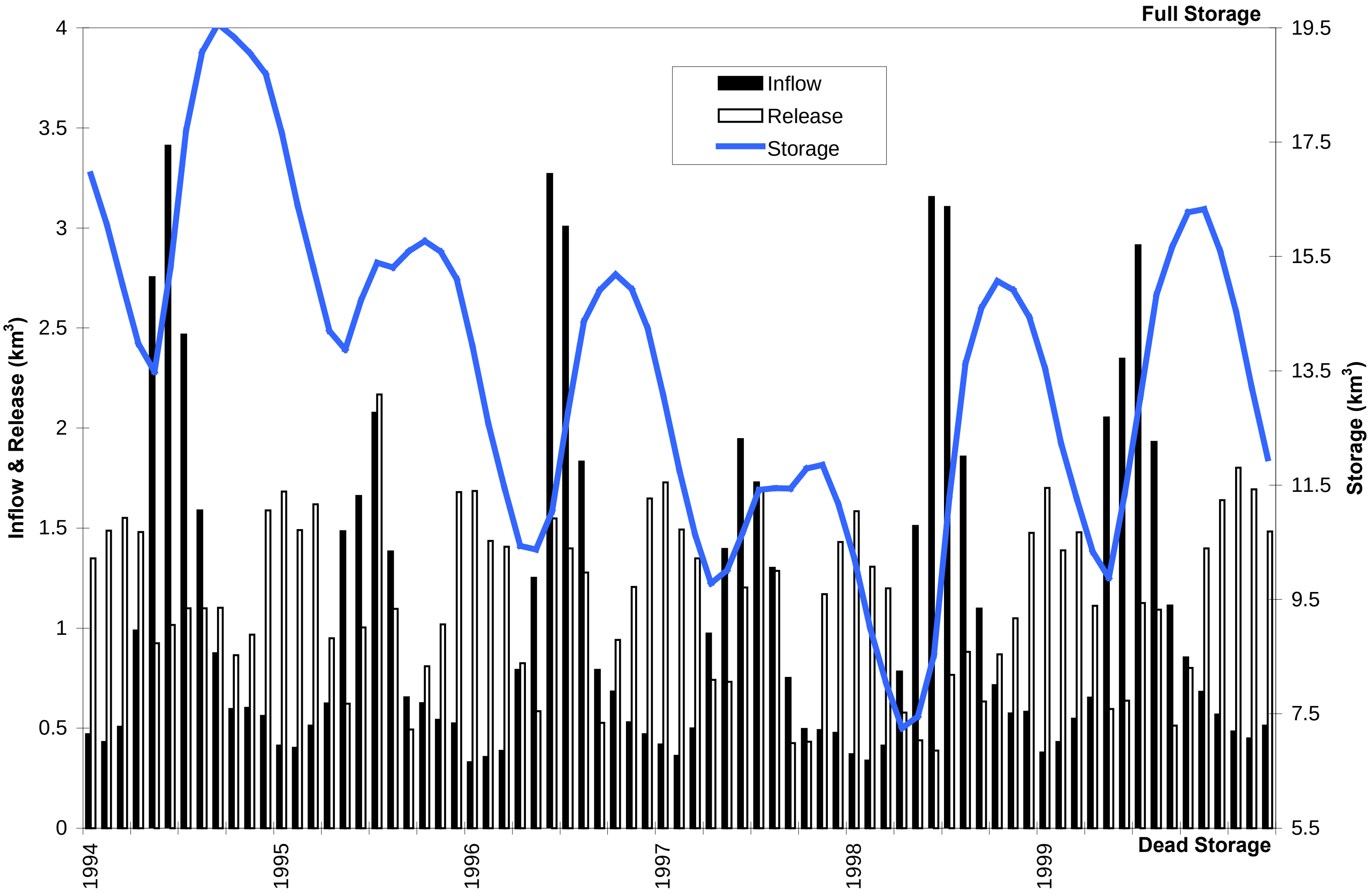
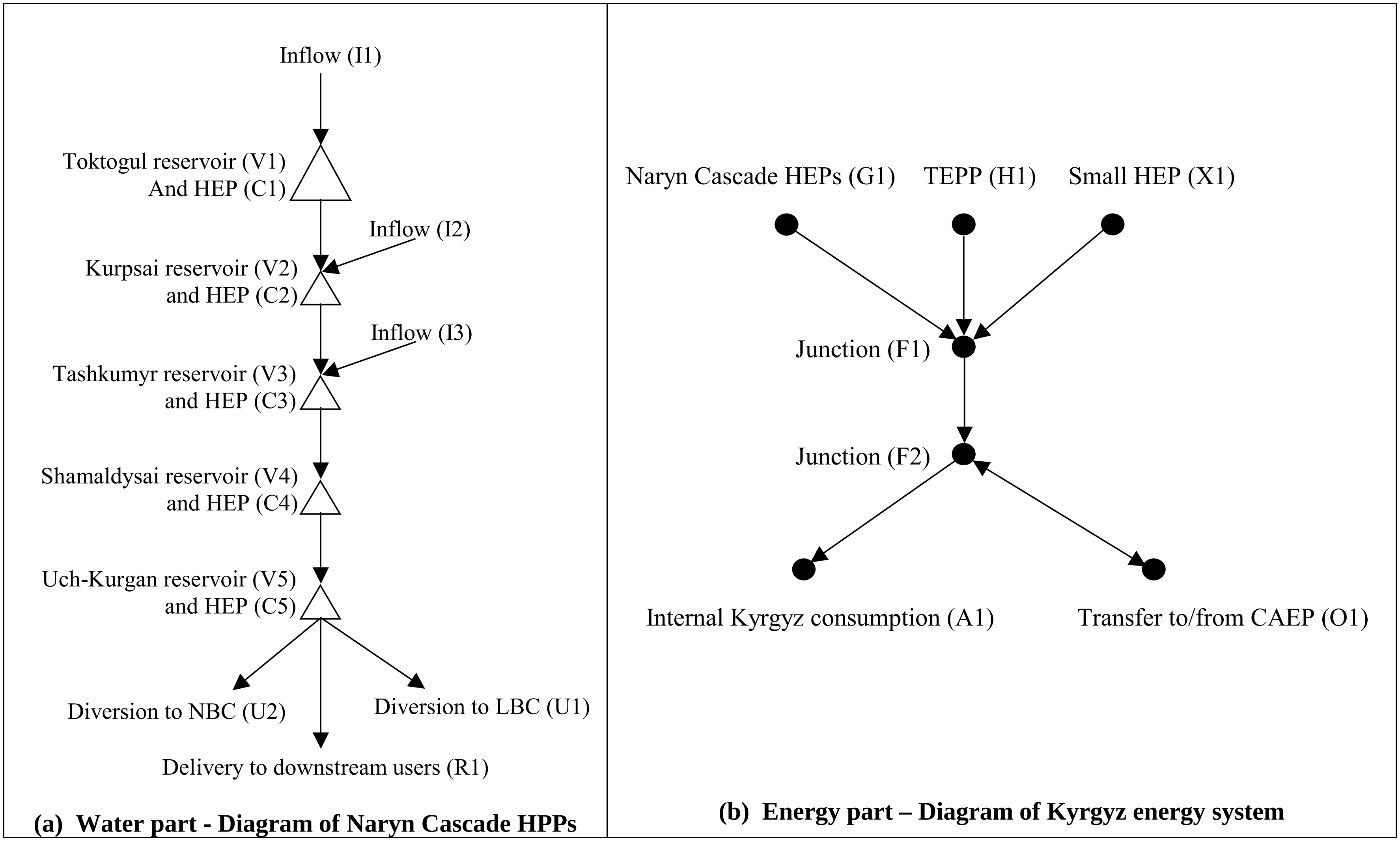


Figure 4. Toktogul reservoir operation 1994-99.



(a) Water part - Diagram of Naryn Cascade HPPs

(b) Energy part – Diagram of Kyrgyz energy system

Figure 5. Diagram of the Naryn Cascade HPPs

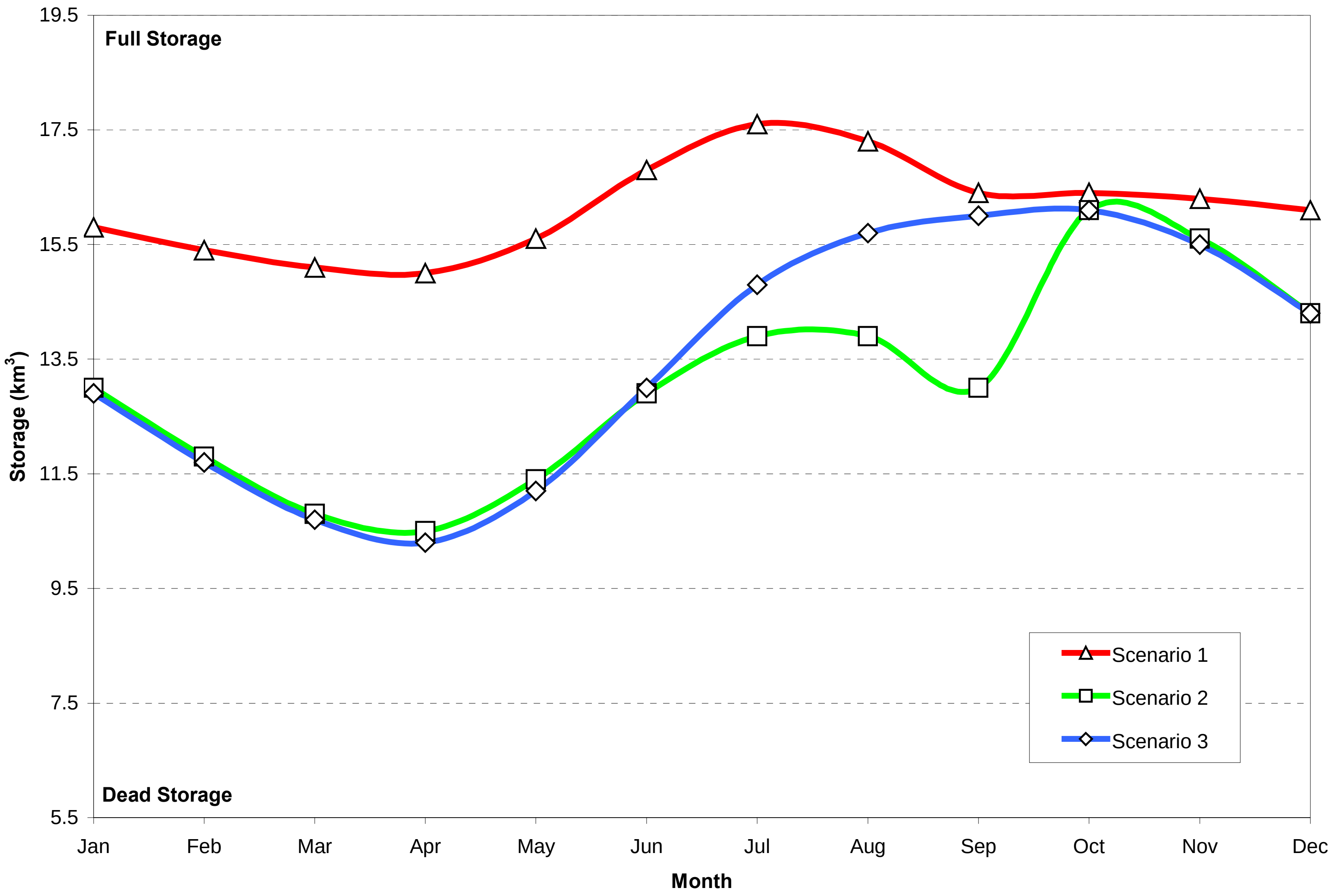


Figure 6. Toktogul reservoir operation under three scenarios.

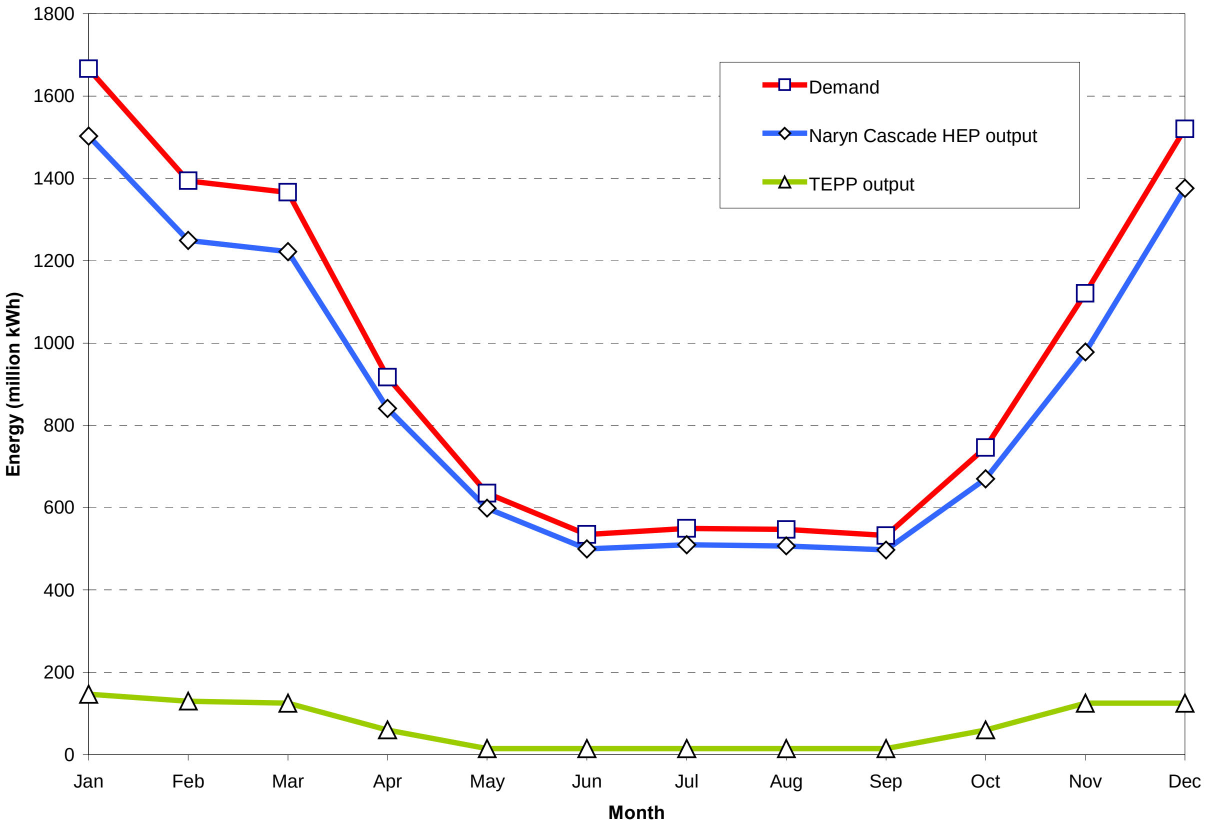


Figure 7. Kyrgyz energy balance under Scenario 1.

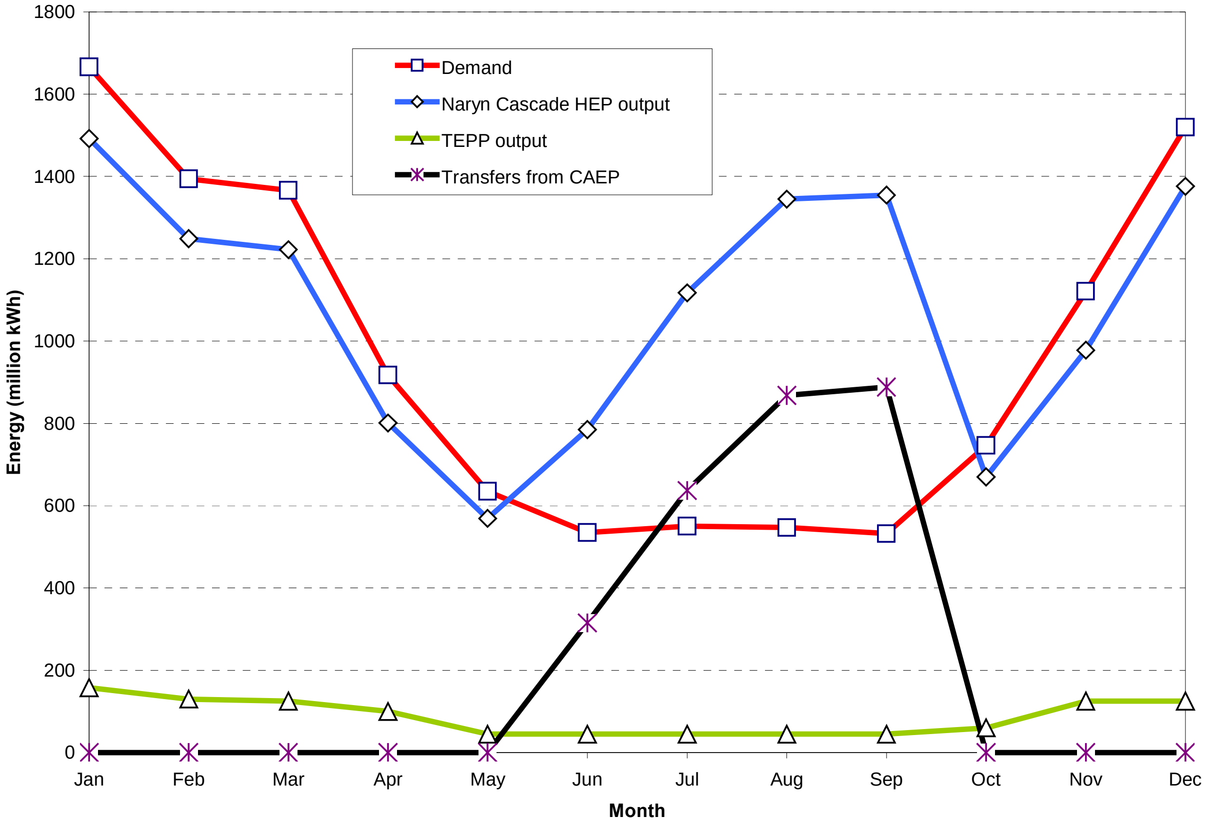


Figure 8. Kyrgyz energy balance under Scenario 2 (transfer from CAEP "+" = export; "-" = import)

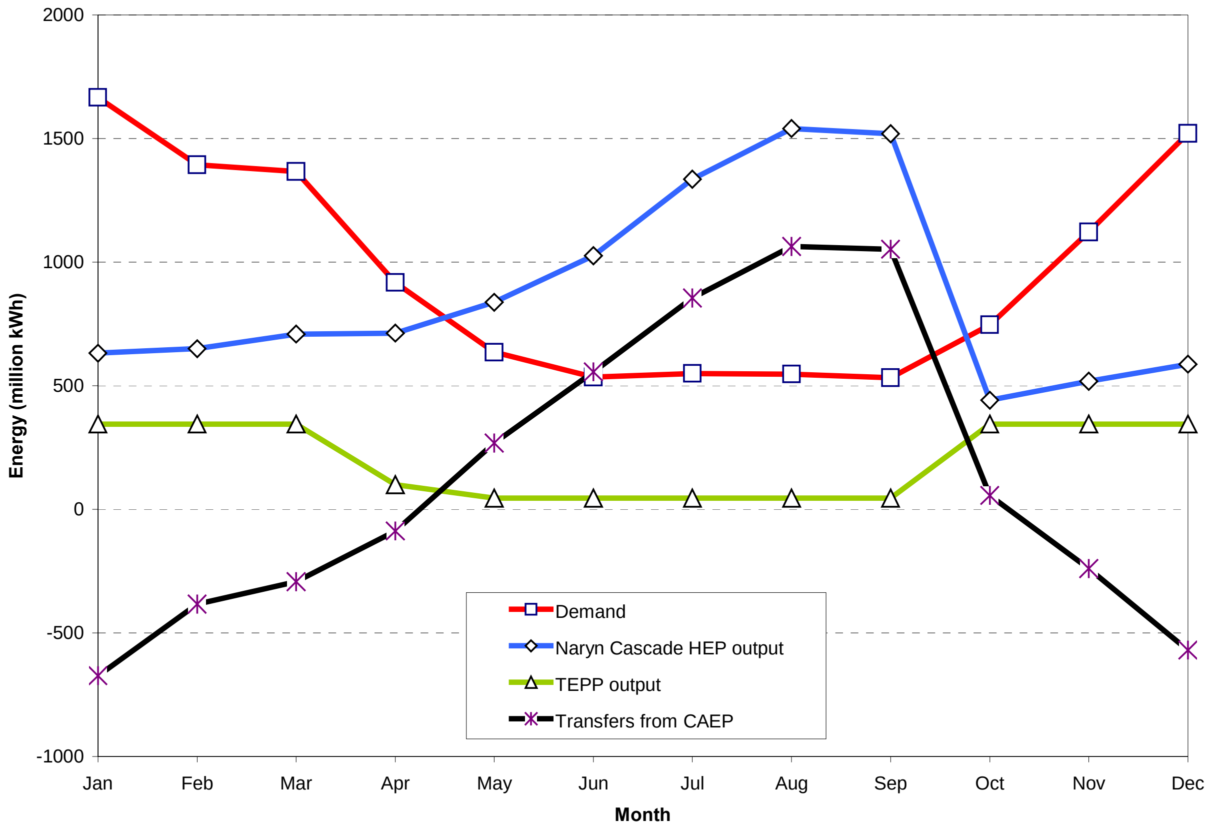


Figure 9. Kyrgyz energy balance under Scenario 3 (transfer from CAEP "+" = export; "-" = import)

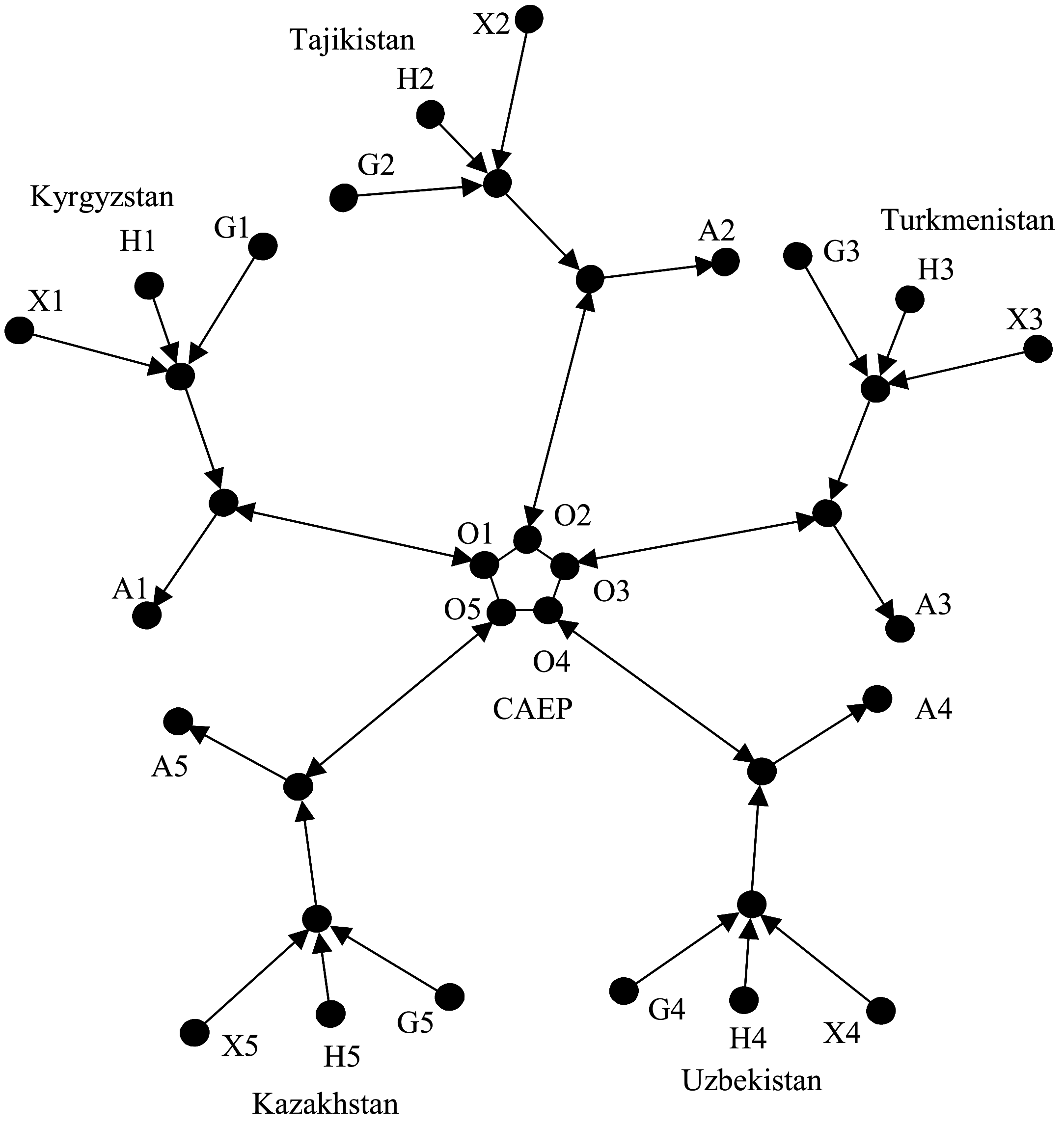


Figure 10. Diagram of the energy part of the Central Asian Water and Energy model.