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Working Paper
Multiobjective Water Resource Allocation Model for Toktogul Reservoir

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Introduction

The principal surface water sources of the Aral Sea region are the river basins of the Amudarya and Syrdarya. The source of these rivers is in the mountainous republics of Kyrgystan and Tajikistan where water use for energy production competes with water use for agricultural production in the down-river countries of Kazakstan, Turkmenestan, and Uzbekistan and flows into the Aral Sea. The issues surrounding the Aral Sea crisis are international, and policy solutions require regional cooperation among the newly independent Central Asian Republics (CAR). Since water flows among all of the Republics and since it is shared in different ways, there must be significant cooperation among the water sharing Republics, especially in the Syrdarya basin.

One of the major sources of the Syrdarya River is the Naryn River in the mountainous Kyrgyz Republic. This source is controlled by a cascade reservoirs of which Toktogul Reservoir is the major one. The downstream countries do not have much local water source, but they do have large irrigated lands and they must rely on the water releases of the upstream countries. Under the Soviet Union, the management of this river was an intra-national issue and the river was managed by a central authority for the combined benefit of the entire region. The primary benefit derived from the management of the river was the provision of water for irrigated agriculture in Uzbekistan and Kazakstan. Upon the collapse of the Soviet Union in 1991, the river basin was split into four sovereign nations with competing interests in the waters of the Syrdarya River. The Kyrgyz Republic's primary objective in managing the river is to maximize the production of hydroelectric power in from Toktogul reservoir. In conflict with this are the downstream countries, Uzbekistan and Kazakstan, whose objectives are to maximize their utilization of water for irrigation. This situation has led to a major international conflict over the waters of the Syrdarya.

The critical factors affecting this international water management problem are the temporal characteristics associated with the objectives of the upstream and downstream countries. In the Kyrgyz Republic, the peak demand for domestic power occurs in winter, while in the downstream countries, the peak demand for irrigation water occurs in the summer.

The actions of the upstream and the downstream countries are neither totally consistent nor totally in conflict with one another. Since the major runoff period occurs in the summer, the Kyrgyz Republic would like to release some water in the summer period, which helps to meet the downstream irrigation needs; but at the same time, they would like to store water for power generation in the winter when there is little runoff. The Kyrgyz Republic's preferred release during April to September is generally expected to be less than the downstream irrigation requirement, except in a wet year. Generally, the Kyrgyz Republic generates more hydroelectric power in summer months than what they need for domestic use, and in the winter months they have to use thermal power plants to meet the power demand. Therefore they try to export hydroelectric power during the summer months to compensate for the cost of fuel for the thermal power plants in winter.

Since more than one republic is involved in downstream irrigation water allocation, an even distribution of water use rights may be considered equitable. That is to say, in case of a water shortage, it might be fair for various demand sites to share the shortage. On the other hand, for crop irrigation needs, water supply should be even from month to month during the vegtation season. For example, if June irrigation demand is totally satisfied, but only half the irrigation demand is satisfied in July, this will not be good for plant growth. It may be better to deliver, say, 75% of the irrigation demand over in both June and July.

The objective of the work described here is to aid the countries of the Syrdarya River basin to develop a long-term water and hydroelectric power sharing agreement. As part of these activities a policy analysis tool has been developed to help decision makers from the Syrdarya basin republics come to an agreement for the allocation of water releases from Toktogul reservoir on the Syrdarya River. This multicriteria decision analysis tool can be used to promote an understanding of the tradeoffs between water releases made for agricultural production and those made for hydroelectric power generation. The scope of the work addresses the need for the development of a multi-objective screening model to aid in the determination of fair and equitable arrangements for sharing the waters of the Syrdarya River between the CAR countries of Kyrgistan, Uzbekistan, Kazakstan, and Tajikistan. Such a model may prove to be useful in assisting CAR decision makers in negotiating agreements or treaties between the countries of Kyrgistan, Uzbekistan, Kazakstan and Tajikistan over the distribution of releases from the reservoir.

Model Development

The development of a mathematical optimization model for the operation of Toktogul reservoir is described here. It is difficult to express the water management goals of a complex situation such as the Syrdarya river basin as a single objective. While the Aral Sea needs more inflow, the agricultural sectors of Uzbekistan and Kazakstan need a dependable supply of irrigation water, the Kyrgyz Republic needs to produce enough hydroelectric power to meet, at least, their winter heating needs. Even in a year with larger than normal rainfall, conflicts among the various planning objectives may still exist. Therefore, it is appropriate to deal with the problem using a multiple objective (criteria) modeling approach.

The model developed here is to be used to promote the understanding of, and aid in the development of, efficient and sustainable water allocation options for the republics that rely on the Syrdarya river for their water resources and Toktogul reservoir for their hydroelectric power. The goal is to construct a screening tool which can be used to easily and quickly identify good alternatives for water management that can then be discussed, debated, modified, and simulated in greater detail.

The model considers water management objectives for power generation in the upstream country and irrigation water supply for the downstream countries. To incorporate the complexities discussed above, we include the following items in the objective function:

- Maximize total power generation in the whole planning period;
- Minimize power deficit in winter periods;
- Maximize water supply for irrigation; and
- Minimize the spatial and temporal divergence of water supply to irrigation.

By integrating these objectives with the system's physical, political, and operational constraints in an optimization model, one can analyze the tradeoffs between the conflicting objectives of flow to the Aral Sea, the satisfaction of agricultural water demand, and the generation of hydroelectric power and develop a number of water allocation scenarios to aid decision making.

Water Allocation Network

The abstract water allocation network which forms the basis for the mathematical optimization model of Toktogul reservoir is shown in Figure 1, illustrating all of the associated river and tributary nodes, water sources, and water demand sites considered in the model.

Water Supply Data

The available sources of groundwater supply considered in the model are listed in Table 1. Water availability for the basin in various years corresponding to different hydrological conditions of dry (total supply = 25.1 km^3/yr), normal (total supply = 42.4 km^3/yr), and wet (total supply = 54.1 km^3/yr) is listed in Table 2 and plotted in Figure 2. Note that the water availability in a normal year is less than the demand.

Table 1. Groundwater Supply in the Syrdarya Basin (km^3/yr) [Raskin et al., 1992]

Source	Capacity (km^3/yr)
Naryn	1.0
Fergana	4.8
Middle Syrdarya	1.0
Chakir	1.0
Artur	0.25
Lower Syrdarya	0.25
Total	8.3

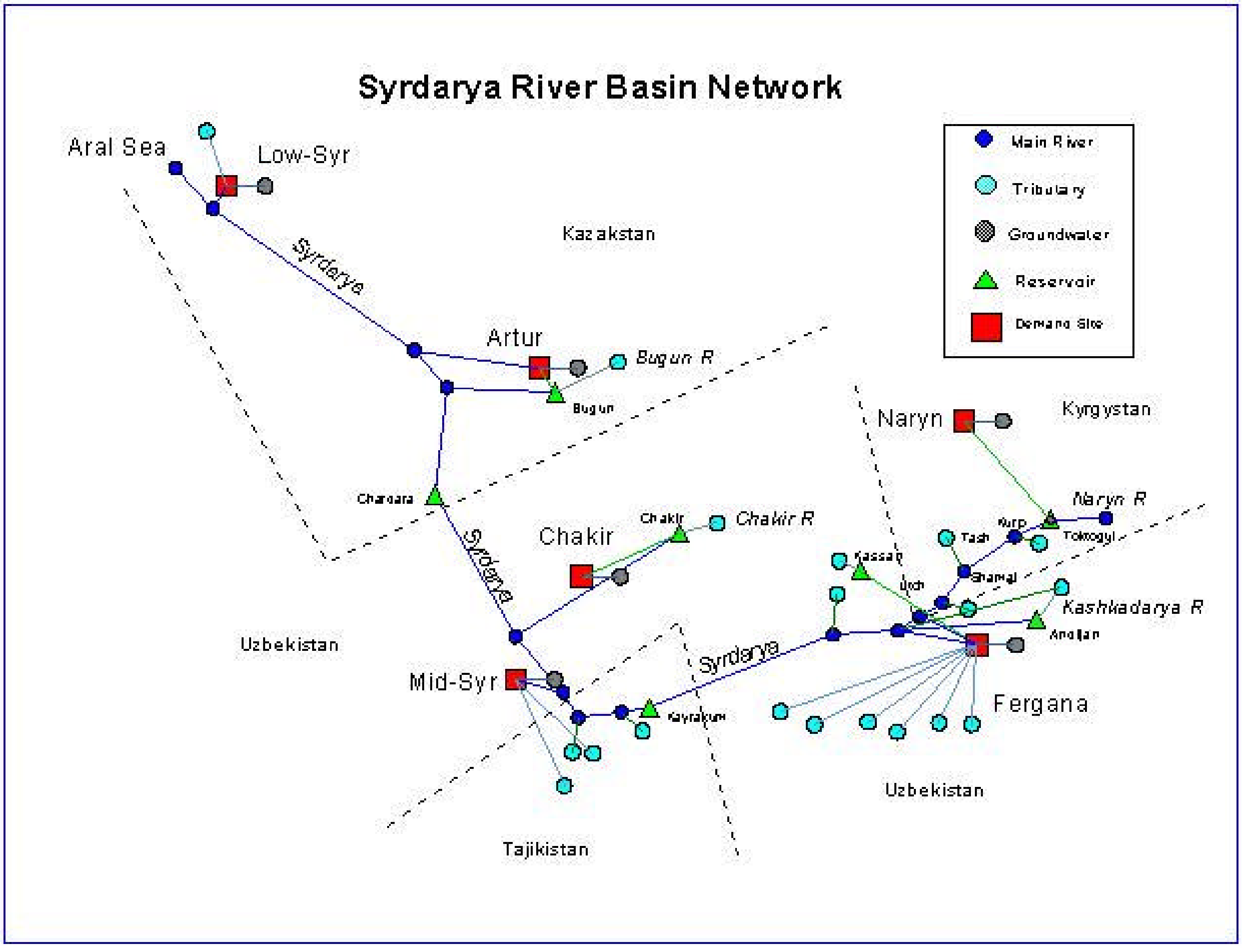

Figure 1. Toktogul system network.

Table 2. Water Supply (km^3/yr) in the Syrdarya River Basin [Raskin et al., 1992]

Wet year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Chakir R	0.29	0.28	0.54	1.15	2.28	3.00	2.64	1.93	0.98	0.62	0.51	0.42	14.64
Main R	0.27	0.31	0.46	0.49	1.54	2.88	3.57	2.18	0.99	0.73	0.61	0.49	14.53
Karadarya R	0.21	0.23	0.68	1.39	2.21	2.51	2.07	1.22	0.58	0.53	0.63	0.48	12.73
Bugun R	0.19	0.15	0.25	0.47	0.41	0.41	0.35	0.25	0.15	0.13	0.12	0.11	2.98
Karasu_rt	0.05	0.06	0.09	0.27	0.44	0.38	0.24	0.14	0.10	0.09	0.09	0.07	2.02
Sokh R	0.03	0.03	0.03	0.03	0.08	0.22	0.43	0.48	0.20	0.09	0.07	0.05	1.74
Right_trib	0.01	0.01	0.03	0.08	0.22	0.25	0.19	0.18	0.11	0.05	0.05	0.03	1.22
Isfay R	0.03	0.03	0.03	0.03	0.06	0.14	0.23	0.18	0.09	0.07	0.06	0.05	1.00
Low_Syr	0.06	0.04	0.11	0.15	0.06	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.51
Isfara R	0.01	0.01	0.01	0.01	0.03	0.07	0.14	0.16	0.06	0.03	0.02	0.02	0.57
Karasu_lt	0.02	0.01	0.02	0.02	0.05	0.07	0.09	0.08	0.06	0.05	0.04	0.03	0.54
Shahima R	0.01	0.01	0.01	0.01	0.02	0.05	0.08	0.06	0.04	0.03	0.03	0.02	0.39
Kassansay R	0.01	0.01	0.01	0.02	0.07	0.09	0.06	0.03	0.01	0.01	0.01	0.01	0.34
Aksu R	0.02	0.02	0.02	0.02	0.02	0.04	0.06	0.04	0.02	0.03	0.02	0.02	0.32
Abshir R	0.00	0.00	0.01	0.01	0.07	0.09	0.06	0.03	0.01	0.01	0.01	0.01	0.32
Shaydan R	0.00	0.00	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.12
Sanza R	0.00	0.00	0.01	0.02	0.02	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.08
Shirni R	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.06
Total	1.22	1.21	2.30	4.19	7.61	10.26	10.26	7.01	3.44	2.48	2.30	1.82	54.10

Normal year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Chakir R	0.25	0.25	0.37	1.05	2.06	2.40	2.03	1.36	0.66	0.42	0.33	0.33	11.53
Main R	0.24	0.28	0.32	0.44	1.39	2.31	2.75	1.54	0.68	0.50	0.39	0.39	11.22
Karadarya R	0.18	0.21	0.47	1.26	1.99	2.01	1.59	0.86	0.40	0.36	0.41	0.39	10.12
Bugun R	0.16	0.13	0.17	0.43	0.37	0.33	0.27	0.17	0.10	0.09	0.08	0.08	2.39
Karasu_rt	0.04	0.05	0.06	0.24	0.40	0.31	0.19	0.10	0.07	0.06	0.06	0.05	1.63
Sokh R	0.03	0.02	0.02	0.03	0.07	0.18	0.33	0.34	0.14	0.06	0.04	0.04	1.30
Right_trib	0.01	0.01	0.02	0.08	0.20	0.20	0.15	0.13	0.08	0.03	0.03	0.03	0.96
Isfay R	0.03	0.03	0.02	0.02	0.05	0.11	0.18	0.13	0.06	0.05	0.04	0.04	0.76
Low_Syr	0.05	0.04	0.07	0.14	0.06	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.42
Isfara R	0.01	0.01	0.01	0.01	0.02	0.06	0.11	0.11	0.04	0.02	0.01	0.01	0.42
Karasu_lt	0.02	0.01	0.01	0.02	0.05	0.06	0.07	0.06	0.04	0.03	0.02	0.02	0.41
Shahima R	0.01	0.01	0.01	0.01	0.02	0.04	0.06	0.04	0.03	0.02	0.02	0.02	0.29
Kassansay R	0.01	0.00	0.00	0.01	0.07	0.07	0.05	0.02	0.01	0.01	0.01	0.01	0.27
Aksu R	0.02	0.02	0.01	0.02	0.02	0.03	0.05	0.03	0.02	0.02	0.01	0.01	0.25
Abshir R	0.00	0.00	0.00	0.01	0.06	0.07	0.04	0.02	0.01	0.01	0.01	0.01	0.26
Shaydan R	0.00	0.00	0.01	0.02	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.10
Sanza R	0.00	0.00	0.00	0.02	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.07
Shirni R	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.04
Total	1.07	1.10	1.59	3.81	6.85	8.21	7.89	4.94	2.34	1.70	1.49	1.45	42.43

Table 2 (continued). Water Supply (km^3/yr) in the Syrdarya River Basin [Raskin et al., 1992]

Dry year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Chakir R	0.23	0.21	0.28	0.72	1.03	1.20	1.01	0.68	0.40	0.38	0.29	0.28	6.71
Main R	0.21	0.23	0.24	0.31	0.69	1.15	1.37	0.77	0.41	0.45	0.34	0.32	6.50
Karadarya R	0.16	0.17	0.35	0.87	0.99	1.00	0.80	0.43	0.24	0.33	0.36	0.32	6.02
Bugun R	0.15	0.11	0.13	0.30	0.19	0.17	0.14	0.09	0.06	0.08	0.07	0.07	1.53
Karasu_rt	0.04	0.04	0.05	0.17	0.20	0.15	0.09	0.05	0.04	0.06	0.05	0.04	0.98
Sokh R	0.03	0.02	0.02	0.02	0.04	0.09	0.16	0.17	0.08	0.05	0.04	0.03	0.75
Right_trib	0.01	0.01	0.01	0.05	0.10	0.10	0.07	0.06	0.05	0.03	0.03	0.02	0.55
Isfay R	0.02	0.02	0.02	0.02	0.03	0.05	0.09	0.06	0.04	0.04	0.04	0.03	0.46
Low_Syr	0.05	0.03	0.06	0.10	0.03	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.30
Isfara R	0.01	0.01	0.01	0.01	0.01	0.03	0.05	0.06	0.03	0.02	0.01	0.01	0.24
Karasu_lt	0.01	0.01	0.01	0.01	0.02	0.03	0.04	0.03	0.02	0.03	0.02	0.02	0.25
Shahima R	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.18
Kassansay R	0.01	0.00	0.00	0.01	0.03	0.04	0.02	0.01	0.01	0.01	0.01	0.01	0.15
Aksu R	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.16
Abshir R	0.00	0.00	0.00	0.01	0.03	0.03	0.02	0.01	0.01	0.01	0.01	0.00	0.14
Shaydan R	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.06
Sanza R	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
Shirni R	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
Total	0.96	0.89	1.21	2.63	3.43	4.10	3.94	2.47	1.41	1.53	1.30	1.21	25.06

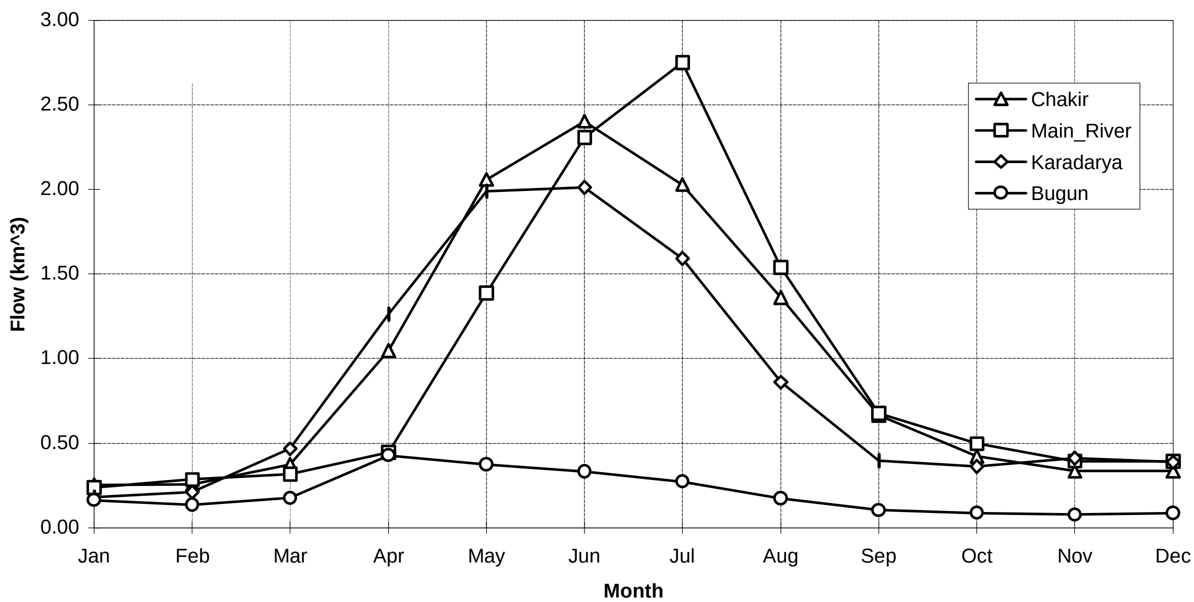

Figure 2. Water supply (km^3/yr) in the Syrdarya River basin under a “normal” hydrologic scenario [Raskin et al., 1992]

Water Storage Facilities

The major water storage facilities of the Syrdarya basin are listed in Table 3.

Table 3. Major Water Storage Facilities of the Syrdarya Basin.

Reservoir	Active storage capacity (km^3)	Dead storage capacity (km^3)
Charda	4.7	1.0
Bugun	0.37	0.007
Toktogul	14.0	5.5
Kassan	0.25	0.02
Andjan	1.64	0.15
Chakir	2.08	0.35
Kayrakum	2.55	1.48
Utchkurgan	0.012	0.04
Kurpskaya	0.0288	0.341
Tashkumur	0.006	0.134
Shamli	0.005	0.039
Farhad	0.30	0.15

Water Demand Data

Irrigation and nonirrigation demand

The source of much of the water demand data used in the model presented here is the data base of the Tellus Institute WEAP (Water Evaluation and Planning System) model for the simulation of water supply and demand in the Aral Sea region [*Raskin et al.*, 1992]. Figure 1 illustrates the network representation of the Syrdarya River basin model, showing all river and tributary nodes, water sources, and water demand sites included in the model. Table 4 lists and Figure 3 illustrates these water demands, including all losses (total demand = 43.77 km^3/yr). It is obvious that these demands should be updates in light of more recent data and this is the subject of current work.

Table 4. Water Demands (km^3/yr) in the Syrdarya River Basin [Raskin et al., 1992]

Demand Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Naryn	0.09	0.09	0.16	0.12	0.27	0.33	0.42	0.37	0.13	0.08	0.06	0.09	2.22
Fergana	0.56	0.57	1.05	0.76	1.71	2.12	2.71	2.36	0.84	0.52	0.40	0.57	14.17
Middle Syrdarya	0.40	0.40	0.75	0.54	1.21	1.50	1.92	1.67	0.60	0.37	0.28	0.40	10.04
Chakir	0.35	0.36	0.67	0.48	1.08	1.34	1.72	1.50	0.53	0.33	0.25	0.36	8.98
Artur	0.10	0.10	0.19	0.14	0.31	0.39	0.50	0.43	0.15	0.09	0.07	0.10	2.59
Lower Syrdarya	0.23	0.23	0.43	0.31	0.70	0.86	1.10	0.96	0.34	0.21	0.16	0.23	5.77
Total	1.73	1.75	3.25	2.33	5.28	6.55	8.38	7.30	2.60	1.60	1.23	1.76	43.77

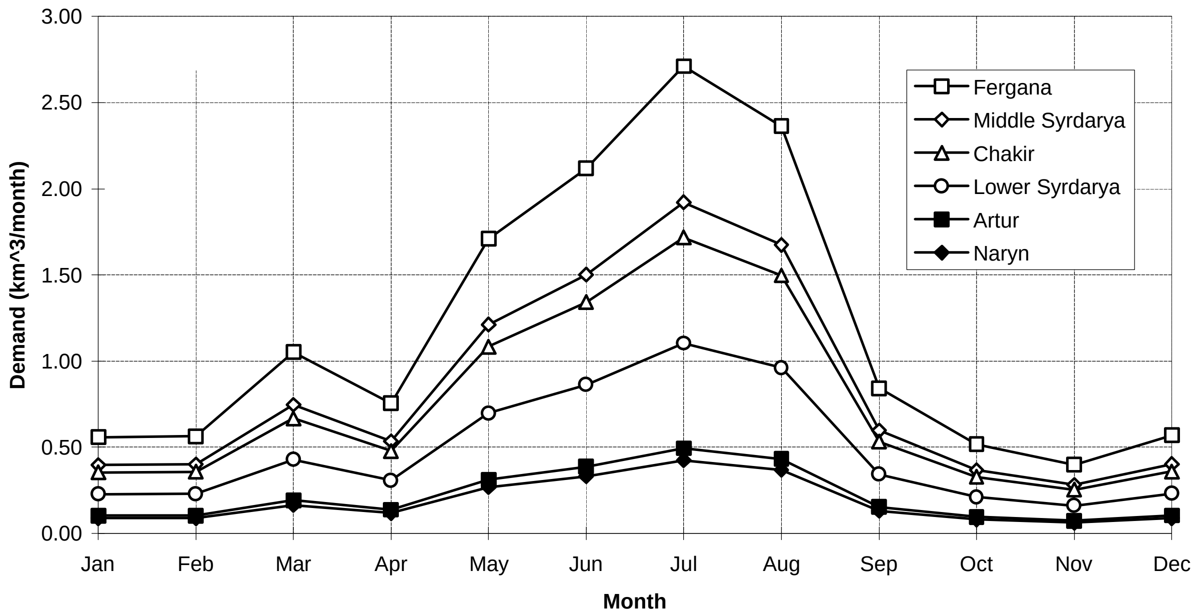

Figure 3. Water Demands (km^3/yr) in the Syrdarya River Basin [Raskin et al., 1992]

Several assumptions have been made in order to accommodate these demands in the model, including:

- Water demands are constant over the modeling period.
- Water demand in November, December, January, and February are primarily for non-irrigation use, e.g., municipal water supply. In the model, it is assumed that the water demand in these months must be totally satisfied.
- Water demand in the Naryn district is assumed to be totally satisfied in all periods.

Aral Sea water demand

In order to consider the Aral Sea as a separate “user” of water, the historic record of flows in the Syrdarya River at Kazalinsk were used as a measure of the flows to the sea. A summary of these flows are shown in Table 5 and Figures 4 - 5.

Table 5. Summary of flows (km^3/mo) in the Syrdarya River at Kazalinsk [P. Micklin, personal communication, 1996].

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total (km^3/yr)
1910-20	0.68	0.81	0.87	1.39	1.55	1.67	1.52	1.32	1.14	0.94	0.87	0.9	13.68
1920-30	0.83	0.7	1.15	1.52	1.95	1.81	1.7	1.46	1.04	0.93	1.02	0.95	15.06
1930-34	0.89	1.21	1.48	1.76	1.98	2.07	2.07	1.8	1.22	1.19	1.2	0.89	17.76
1935-39	0.99	1.22	1.41	1.76	2.11	2.27	2.04	1.47	1.1	1.13	1.27	1.02	17.78
1940-44	0.96	0.87	1.17	1.58	1.52	1.76	1.69	1.04	0.74	0.77	1.12	1.03	14.24
1945-49	0.67	0.85	1.07	1.49	1.73	1.73	1.72	1.2	0.85	0.93	1.18	0.94	14.38
1950-54	0.87	1.03	1.33	1.86	1.76	2	1.84	1.53	1.12	1.26	1.39	0.91	16.92
1955-59	0.71	1.05	1.36	2.15	1.97	1.75	1.49	1.14	0.81	0.95	1.22	1.05	15.65
1960-64	0.77	0.95	1.26	1.67	1.54	1.97	1.28	0.87	0.78	0.86	0.95	0.78	13.66
1965-69	0.61	0.63	0.79	1.11	1.02	0.78	0.86	0.87	0.75	0.72	0.74	0.66	9.53
1970-74	0.46	0.6	0.8	1.01	0.75	0.52	0.46	0.59	0.71	0.48	0.42	0.37	7.17
1975-79	0.15	0.13	0.17	0.08	0.08	0.1	0.07	0.1	0.12	0.1	0.1	0.15	1.34

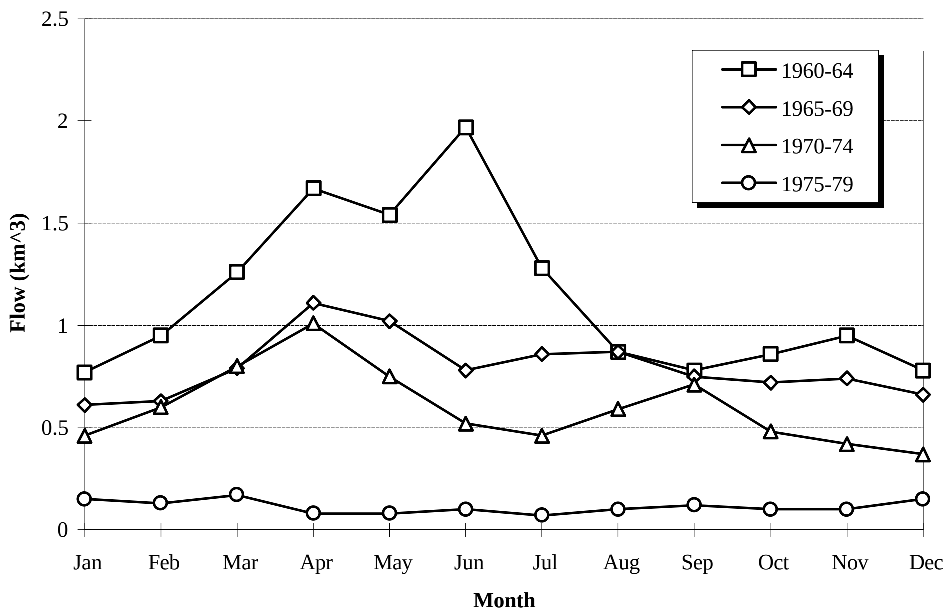

Figure 4. Summary of monthly flows (km^3/mo) in the Syrdarya River at Kazalinsk [P. Micklin, personal communication, 1996].

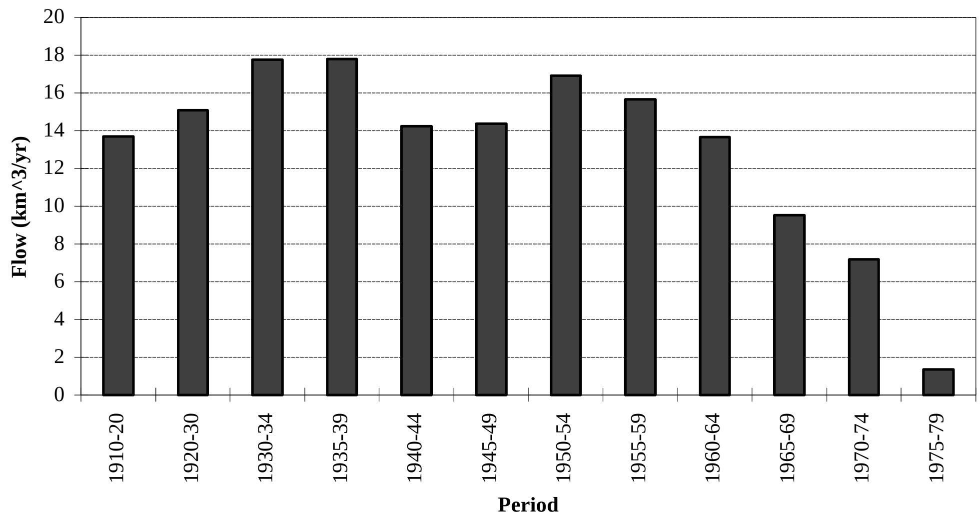

Figure 5. Summary of annual flows (km^3/yr) in the Syrdarya River at Kazalinsk [P. Micklin, personal communication, 1996].

Energy Demand Data

The source of the energy demand data used in the model presented here is the Harza Engineering report of hydropower development potential for the Kyrgyz Republic [Harza, 1993]. Figure 1 illustrates the network representation of the Syrdarya River basin model, showing all hydroelectric power stations included in the model. Their characteristics are listed in Table 6.

Table 6. Power Station Data for the Syrdarya River Basin

Station	Production capacity (MW)	Efficiency (%)	Maximum pool elevation (m)	Tailwater elevation (m)	Head on turbine (m)
Toktogul	864	0.85	900	700	200
Kurpskaya	576	0.85	724	618	106
Tashkumur	162	0.85	628	568	60
Shamli	69.12	0.85	572	540	32
Utchkurgan	129.6	0.85	540	504	36

Table 7 and Figure 6 show the energy demands included in the model (total demand = 8050 MWh). These demands have been projected over 5 years using data from the Harza [1993] report. The hydroelectric power demand is calculated based on the total power demand projection in next three or five years given in the report by Harza Engineering [Harza, 1993] (refer to hydropower power demand calculation). Hydroelectric power production is assumed cover 80% of the total power demand [Harza, 1993] with thermal power plants making up the remainder. It is also assumed that the thermal power plants are used only in winter months (Nov., Dec., Jan., and Feb.).

Table 7. Energy Demand in the Syrdarya River Basin [Harza, 1993].

	1996	1997	1998	1999	2000
Total power demand (GWh)	11,105	11,221	11,359	11,513	11,685
Rate of increase (%)	1.000	1.045	1.230	1.356	1.494
Thermal power (GWh)	2,221.0	2,244.2	2,271.8	2,302.6	2,337.0
Hydroelectric demand (GWh)					
Annual	8,884.0	8,976.8	9,087.2	9,210.4	9,348.0
Jan	1,020.5	1,031.2	1,043.8	1,058.0	1,073.8
Feb	1,498.3	1,513.9	1,532.5	1,553.3	1,576.5
Mar	802.4	810.8	820.8	831.9	844.3
Apr	713.8	721.3	730.1	740.0	751.1
May	532.3	537.8	544.5	551.8	560.1
Jun	499.5	504.7	510.9	517.8	525.5
Jul	522.0	527.5	534.0	541.2	549.3
Aug	512.8	518.1	524.5	531.6	539.6
Sep	512.8	518.1	524.5	531.6	539.6
Oct	690.2	697.4	706.0	715.6	726.3
Nov	635.9	642.5	650.4	659.2	669.1
Dec	943.6	953.4	965.2	978.2	992.9

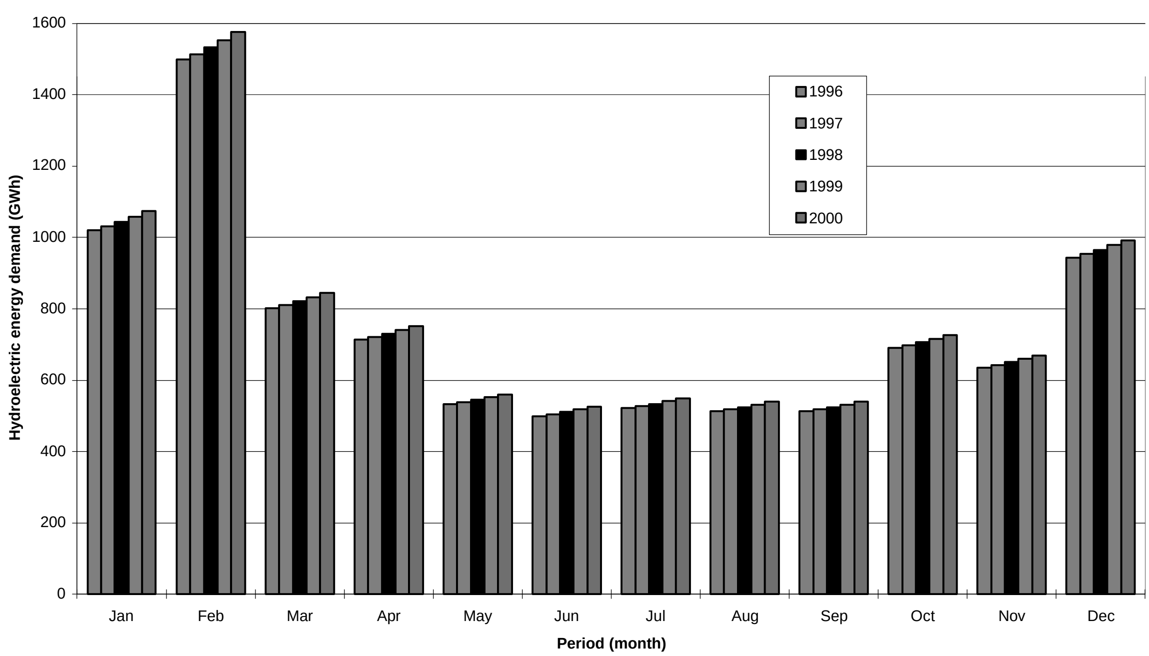

Figure 6. Projected energy demand (GWh/month) in the Syrdarya River basin for 1996 - 2000 [Harza, 1993].

Model Structure

Indices and Sets

Several indices and sets appear in the water allocation model equations. These define the basic elements of the model such as time periods, river nodes, links between elements of the system and so on.

<u>Indices</u>

pd	time periods (month)
rn	river nodes
dem	demand sites
rev	reservoirs
pwst	power stations
sou	surface water sources
gd	groundwater sources

<u>Links</u>

GDLINK	aquifers to demand sites
NDLINK	river to demand sites
NGLINK	river to aquifers
NRLINK	river to reservoirs
RDLINK	reservoirs to demand sites
RGLINK	reservoirs to aquifers
RNLINK	reservoirs to river
RPLINK	reservoirs and power stations
RRLINK	reservoirs to reservoirs
RRLINK	reservoirs to reservoirs
RVLINK	upstream river node to river node
SDLINK	tributaries to demand sites
SGLINK	tributaries to aquifers
SNLINK	tributaries to rivers
SRLINK	tributaries to reservoirs

Data

Many data are required to specify the physical capacities of the elements of the water resource system associated with Toktogul reservoir. These include:

<u>Source characteristics</u>

PUMP_CP(gd)	groundwater pumping capacity
R_UP(rev)	reservoir active storage upper bound

Loss coefficients

LOSS_N_G(rn, gd)	water loss coefficients from river to groundwater
LOSS_R_G(rev, gd)	water loss coefficients from a reservoir to groundwater
LOSS_S_G(sou, gd)	water loss coefficients from a tributary to groundwater
R_EVAP(rev, pd)	water evaporation in reservoirs

Power stations parameters

PWST_CP(pwst)	power station production capacity
PWST_EF(pwst)	power station production efficiency
PWST_TE(pwst)	power station tail water elevation.
PW_GOAL(pd)	monthly power production goal

Water demand and supply

DM(dem, pd)	monthly irrigation and nonirrigation water demand
SOURCE(sou, pd)	monthly surface water sources in tributaries and canals

Variables

Several system variables are necessary to define the dynamic characteristics of the system such as flow through river nodes, storage in reservoirs, and so on.

AREA(rev, pd)	surface area of reservoir *rev* in period *pd*
FLOW(rn, pd)	flow through river node *rn* in period *pd*
GWP(gd, dem, pd)	groundwater pumped from source *gd* to demand *dem* in period *pd*
H(rev, pd)	hydraulic head in reservoir *rev* in period *pd*
N_DMS(rn, dem, pd)	flow from river node *rn* to a demand site *dem* in period *pd*
POWER(pwst, pd)	power generation at station *pwst* in period *pd*
RES_D(rev,dem, pd)	flow from reservoir *rev* to demand site *dem* in period *pd*
RES_N(rev, rn, pd)	flow from reservoir *rev* to river node *rn* in period *pd*
RES_R(rev, rev, pd)*	release from reservoir *rev* to downstream reservoir *rev** in period *pd*
RES_ST(rev, pd)	storage in reservoir *rev* in period *pd*
RI(dem, pd)	ratio of water supplied to that demanded at site *dem* in period *pd*
RMI(dem)	minimum value of RI among all demand sites
RMIN(pd)	minimum value of RI over all periods
RPMIN	minimum ratio of power generation to power demand in all periods
S_DMS(sou,dem, pd)	flow from tributary node *sou* to a demand *dem* in period *pd*
S_RES(sou, rev, pd)	flow from tributary node *sou* to a reservoir *rev* in period *pd*
S_RIV(sou, rn, pd)	flow from tributary node *sou* to a river node *rn* in period *pd*

Objective Functions

The optimization model includes multiple objectives:

1. Maximize the satisfaction of water demand at all demand sites; to achieve this, the model maximizes *RI*, the ratio of supply to demand over all periods and demand sites

$$Z_1 = \sum_{dem} \sum_{pd} \frac{RI(dem, pd) DM(dem, pd)}{TDM(dem)}$$

2. Minimize the difference in water deficits among all demand sites. This equalizes the rights to water, i.e., ensures that demand sites share the available water equally, and on the other hand distributes the risk of a water shortage as evenly as possible among periods. To achieve this goal, the model maximizes *RMI*, the minimum *RI* in one period over all demand sites, and maximizes *RMIN*, the minimum *RI* of one demand site over all periods.

$$Z_2 = \sum_{dem} RMI(dem) + \sum_{pd} RMIN(pd)$$

3. Maximize the minimum hydropower generation over all periods

$$Z_3 = RPMIN$$

4. Maximize hydropower generation for each station and each period

$$Z_4 = \sum_{pd} \sum_{pwst} \frac{POWER(pwst, pd)}{PW\_GOAL(pd)}$$

These objectives are combined into a single objective function by multiplying each by a weight reflecting the importance of that objective and forming a linear combination of the objectives

$$Maximize\ Z = w_1 Z_1 + w_2 Z_2 + w_3 Z_3 + w_4 Z_4$$

Constraints

There are three kinds of constraints in the optimization model, physical constraints (e.g., mass balances), policy constraints (e.g., upper and lower bounds on variables), and system control constraints (e.g., to maintain feasibility). The physical constraints comprise the bulk of the model constraints. The concept of this kind of constraint is a mass balance of the water in the main river and tributaries, reservoirs and lakes, aquifers and demand sites. The flow of water is described in these mass balance equations. The physical constraints also include some physical limits, such as river and canal diversion capacity, groundwater pumping capacity, and hydropower power generation capacity.

- Water balance at demand site *dem* in period *pd* (definition of *RI*)

$$\sum_{\substack{(sou,dem)\\ \in SDLINK}} S\_DMS(sou,dem,pd) + \sum_{\substack{(rn,dem)\\ \in NDLINK}} N\_DMS(rn,dem,pd)$$

$$+ \sum_{\substack{(rev,dem)\\ \in RDLINK}} RES\_D(rev,dem,pd) + \sum_{\substack{(gd,dem)\\ \in GDLINK}} GWP(gd,dem,pd)$$

$$= RI(dem,pd) * DM(dem,pd)$$

- Water source limit

$$\sum_{\substack{(sou,dem)\\ \in SDLINK}} S\_DMS(sou,dem,pd) + \sum_{\substack{(sou,rn)\\ \in SNLINK}} S\_RIV(sou,rn,pd)$$

$$+ \sum_{\substack{(sou,rev)\\ \in SRLINK}} S\_RES(sou,rev,pd) + \sum_{\substack{(sou,gd)\\ \in SGLINK}} LOSS\_S\_G(sou,pd)$$

$$\leq SOUCE(sou,pd)$$

- Water balance at main river nodes

$$FLOW(rn, pd) = \sum_{\substack{(rn\_up,rn) \\ \in RVLINK}} FLOW(rn\_up, pd) + SOURCE(rn = main\_rv, pd)$$

$$- \sum_{\substack{(rn,gd) \\ \in GDLINK}} LOSS\_N\_G(rn, gd) * FLOW(rn, pd)$$

$$+ \sum_{\substack{(rev,rn) \\ \in RNLINK}} RES\_N(rev, rn, pd) + \sum_{\substack{(sou,rn) \\ \in SNLINK}} S\_RIV(sou, rn, pd)$$

$$+ \sum_{\substack{(rn,dem) \\ \in NDLINK}} N\_DMS(rn, dem, pd)$$

$$- \sum_{\substack{(rn,dem) \\ \in NDLINK}} 0.1 * \left[N\_DMS(rn, dem, pd-1) + N\_DMS(rn, dem, pd = end) \right]$$

- Reservoir water balance

$$RES\_T(rev, pd-1) + \sum_{\substack{(rev\_up,rev) \\ \in RRLINK}} RES\_R(rev\_up, rev, pd)$$

$$+ \sum_{\substack{(sou,rev) \\ \in SRLINK}} S\_RES(sou, rev, pd) + \sum_{\substack{(rn,rev) \\ \in NRLINK}} FLOW(rn, pd)$$

$$= RES\_ST(rev, pd) + R\_EVAP(rev, pd) * AREA(rev, pd)$$

$$+ \sum_{\substack{(rev\_lo,rev) \\ \in RRLINKL}} RES\_R(rev, rev\_lo, pd) + \sum_{\substack{(rev,dem) \\ \in RDLINK}} RES\_D(rev, dem, pd)$$

$$+ \sum_{\substack{(rev,rn) \\ \in RNLINK}} RES\_N(rev, rn, pd)$$

$$+ \sum_{\substack{(rev,gd) \\ \in RGLINK}} LOSS\_R\_G(rev, gd) * RES\_ST(rev, pd)$$

- Groundwater pumping limit

$$\sum_{\substack{(gd,dem) \\ \in GDLINK}} GWP(gd, dem, pd) \leq PUMP\_CP(gd)$$

- Hydroelectric power generation

$$POWER(pwst, pd) \leq \sum_{\substack{(rev,pwst) \\ \in RPLINK}} \left\{ H\_NET(rev, pd) * R\_NET(rev, pd) * PWSTEF(pwst) \right\}$$

where

$$R\_NET(rev, pd) = \sum_{\substack{(rev,rn) \\ \in RNLINK}} RES\_N(rev, rn, pd) + \sum_{\substack{(rev,rev\_lo) \\ \in RRLINKL}} RES\_R(rev, rev\_lo, pd)$$

$$H\_NET(rev, pd) = \frac{H(rev, pd) + H(rev, pd - 1}{2} - PWST\_TE(pwst)$$

- Definition of *RMI* and *RMIN*

RMIN(pd) £ *RI(dem,pd)*

RMI (dem) ‡ *RI(dem,pd)*

- Definition of minimum power production

$$RPMIN \leq \sum_{pwst} \frac{POWER(pwst, pd)}{PW\_GOAL(pd)}$$

- Reservoir storage - head relationship

$$RES\_RT(rev, pd) = B(rev) * H(rev) + C(rev)$$

- Reservoir storage volume - surface area relationship

$$AREA\_VOL(rev, pd) = D(rev) * RES\_ST(rev, pd) + E(rev)$$

- Minimum flow to the Aral Sea

$$\sum_{pd} FLOW(rn = 'low\_syr', pd) \geq ARAL\_FL$$

- Other considerations and constraints

1. A lower bound can be set for the inflow to the Aral Sea from the Syrdarya River. This item could also be put in the objective function to analyze the relationship between this ecological objective and other objectives such as irrigation and power generation.

2. The maximum release for Chardara reservoir can be set (e.g., at 342 m^3/s) to prevent downstream flooding in Kazakstan and damage to local facilities.

3. The dead storage of Kayrakum reservoir can be set (e.g., at 1.4 km^3) to prevent excessive pumping to satisfy local water demands in Tajikistan.

4. The lower bound for summer release from Toktogul reservoir can be set (e.g., according the agreement between Kysgystan and Uzbekistan in 1995).

5. The initial reservoir storage volumes can be set according to users' attitudes. Setting the initial reservoir storage equal to dead storage is the worst case, and setting it equal to full storage is the best case. It is suggested to use a long-term average in a winter month (the model begins from Jan.).

6. It is assumed that the ending storage is related to the hydrologic level of the ending year. If the ending year is dry, then the storage in Dec. of the ending year is going to be equal to the dead storage; however, if the ending year is normal or wet, the ending storage may take the long-term average value of a normal or wet year, respectively.

Assumptions and Limitations of the Model

A model for water allocation decision support in the Syrdarya River basin with the major focus being the operation of the Toktogul reservoir has been developed. This model describes the major physical processes in the Srydarya basin, including flow in the main river and tributaries, reservoir operation and hydropower generation, irrigation, aquifer operation and interaction between surface water and groundwater, water distribution and water return. The time step used in the model is one month, which may be suitable for water resources allocation on a macro-level, but may not have meaning for some of the physical processes (e.g., flood control). The interaction of surface water and groundwater has been greatly simplified. We treat the aquifers as separate groundwater reservoirs without flow links between them. There is infiltration from surface water sources such as reservoirs, streams and canals to aquifers, but not in the reverse direction.

Results

Using the model, three cases were examined in detail, each with a different objective:

A. **Irrigation**– satisfaction of irrigation demands with no consideration of power demand or production;
B. **Irrigation + Power** – satisfaction of irrigation demands and Kyrgyz power demands; and
C. **Power** – maximization of power production while satisfying Kyrgyz power demands, with no consideration of irrigation demands.

Flow to the Aral Sea during the 1995-96 year was about 5 km^3. For each of the three cases, five variants of flow to the Aral Sea were considered:

Variant	Flow to the Aral Sea (km^3/yr)
1	0.00
2	1.35
3	4.05
4	7.17
5	9.33

The cases consider all the reservoirs in the basin to be half-full at the beginning of the modeled period of five years. For each case, several items were calculated: the total supply and deficit of water to agricultural production, the total amount of power generated and any resulting deficit of power, and the net benefits resulting from agricultural production, power generation and the flow to the Aral Sea. The results, in terms of water allocation and energy production, of running the model for the three cases and five variants of each case are shown in Table 8.

Table 8. Model results for Five Flow Variants of Three Cases.

	Variant				
Case	**1**	**2**	**3**	**4**	**5**
(Flow to Aral Sea, km3/yr)	(0.00)	(1.35)	(4.05)	(7.17)	(9.33)
A (Irrigation)					
Water Supply (km^3/yr)	43.8	43.4	40.35	36.8	34.26
Deficit (km^3/yr)	0.0	(0.286)	(3.41)	(7.01)	(9.51)
Power Supply (GWh/yr)	8986	8887	9022	8919	8927
Deficit (GWh/yr)	(580)	(2824)	(2455)	(1904)	(1948)
B (Irrigation + Power)					

Water Supply (km^3/yr)	42.9	42.6	39.3	36.1	33.1
Deficit (km^3/yr)	(0.87)	(1.1)	(4.5)	(7.7)	(10.7)
Power Supply (GWh/yr)	9108	9108	9108	9108	9108
Deficit (GWh/yr)	0.0	0.0	0.0	0.0	0.0
C (Power)					
Water Supply (km^3/yr)	39.6	38.5	36.0	33.5	31.4
Deficit (km^3/yr)	(4.17)	(5.27)	(7.17)	(10.3)	(12.34)
Power Supply (GWh/yr)	9657	9657	9657	9657	9657
Deficit (GWh/yr)	0.0	0.0	0.0	0.0	0.0

Figures 7 and 8 show, respectively, the model calculated releases from and storage in Toktogul Reservoir under the three cases for a required flow to the Aral Sea of 9.33 km3/yr. From Figure 7 one can see that the major difference in the release policy from Toktogul is that Cases B (irrigation + power) and C (power first) requires larger winter releases and smaller summer releases than Case A (water first). There is little noticeable difference between the release policies for Cases B and C. Figure 8 shows clearly that Cases B and C maintain higher Toktogul storage levels later in the vegetation period that does Case A. In the later years, there is no noticeable difference between Cases B and C.

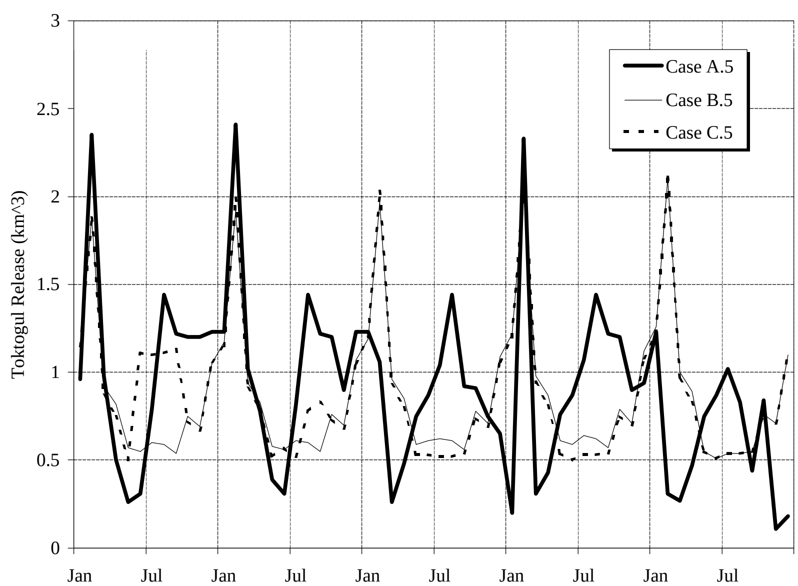

Figure 7. Toktogul reservoir releases for Cases A.5 (Average annual releases =10.97 km3/yr), B.5 (Ave. ann. releases =10.44 km3/yr), and C.5 (Ave. ann. releases =10.65 km3/yr).

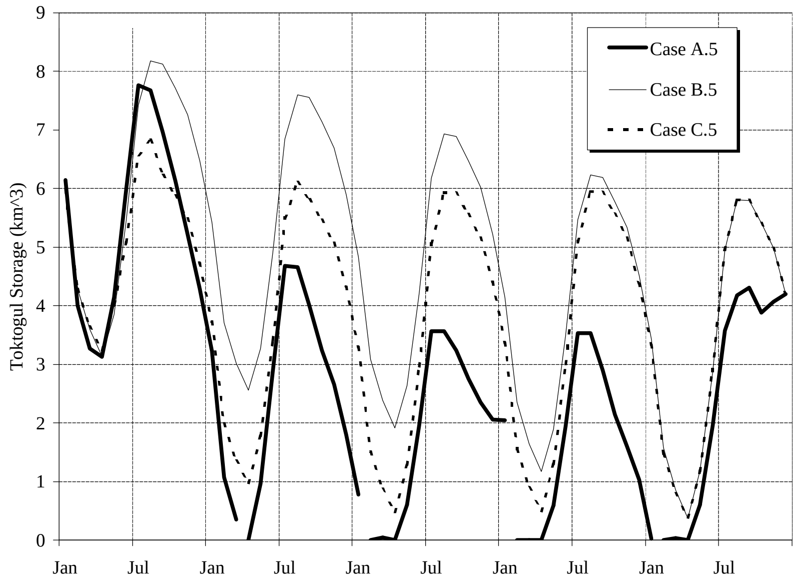

Figure 8. Toktogul Reservoir storage for Cases A.5, B.5, and C.5.

Figure 9 shows the ratio of the generated power to the demanded power for the three Cases with the flow to the Aral Sea required to be at least 9.33 km3/yr (variant 5). Note that the electricity demand increases in the later years so that by year five the demand is 5% greater than in year 1. From the figure we see that in Case A there is a surplus of power generated in the summer months and a deficit of power in the winter months. There is an excess of power generated in the first two years for Case C. In Case B, the ratios of power generated to that demanded are 1.0 for all periods, in Case C, the ratios are 1.0 for all periods except periods June – September for the first two years, in which the ratios are more than 1.0 (up to 2.1). The power generation from Toktogul and the other four stations of the Naryn Cascade is determined by the release*head (storage) relationship. It seems that in the case of this model, the release from Toktogul is more important than the storage level for power generation. This is because the release goes to the downstream stations and causes them to generate more power.

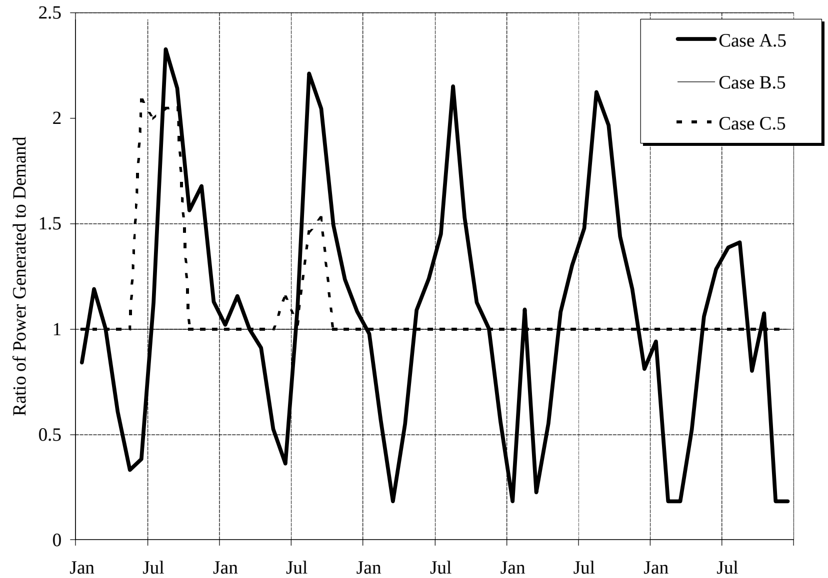

Figure 9. Ratio of power generated through the Nayrn Cascade to power demanded in Kyrgystan for Cases A.5 (Ave. ratio = 1.05), B.5 (Ave. ratio = 1.00), and C.5 (Ave. ratio = 1.09).

Figure 10 illustrates the total amount of water supplied to demand sites over the modeled period. Very little difference is seen for the three cases except for Case C in September and October.

Figure 11 shows the storage levels in Kayrakum Reservoir for the three cases. From this figure we see that, under Case C, the releases from Toktogul Reservoir are being captured in Kayrakum for release in the later months of the vegetation season. The releases from Chardara Reservoir are shown in Figure 12. The average releases for these two reservoirs are greatest for Case B and smallest for Case C. Figures 13 and 14 show the releases from Andijan and Charvak reservoirs. From these figures it is evident that there is a shift in the timing of the releases from these facilities, Andijan releases occur earlier and Charvak releases later in the year under Case C than Case A.

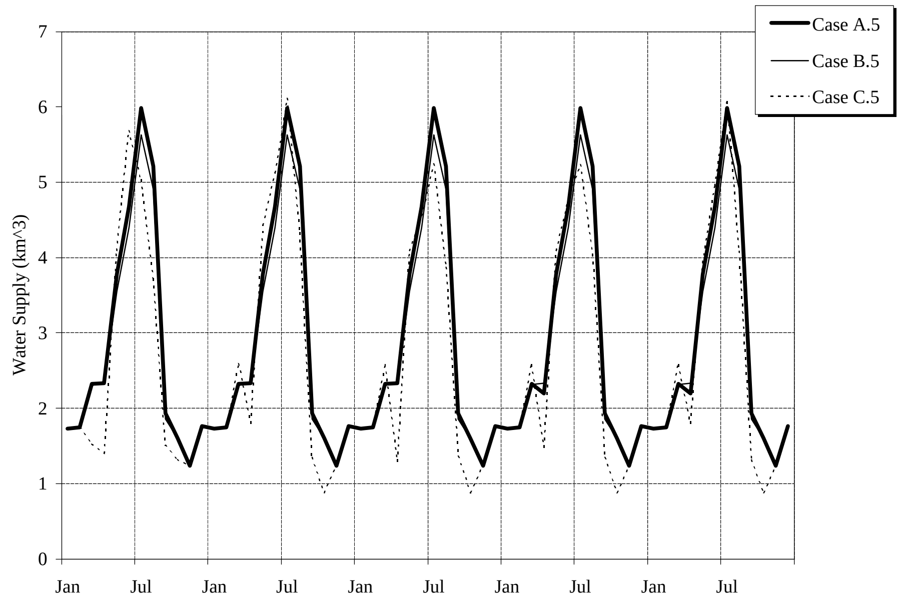

Figure 10. Water supply for Cases A.5, B.5, and C.5.

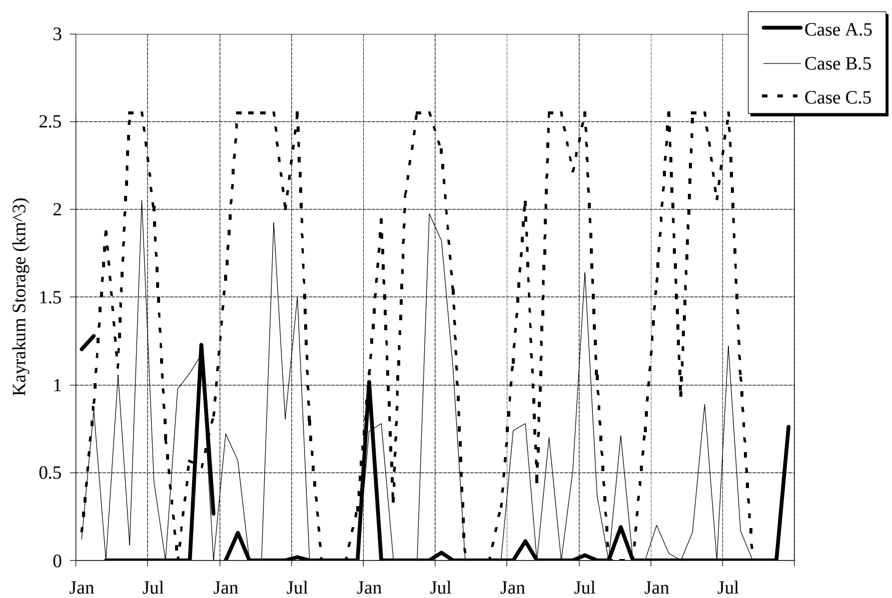

Figure 11. Kayrakum Reservoir storage for Cases A.5 (Ave. ann. releases = 17.70 km3/yr), B.5 (Ave. ann. releases =18.13 km3/yr), and C.5 (Ave. ann. releases =13.43 km3/yr).

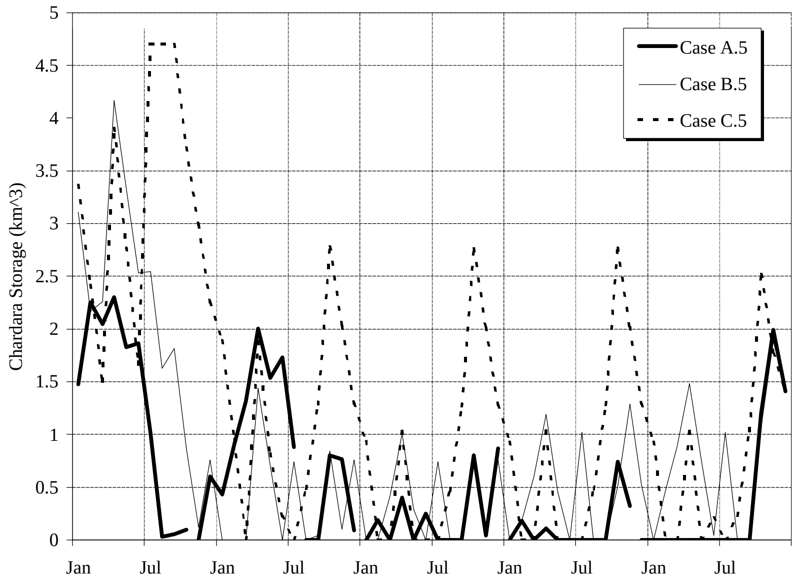

Figure 12. Chardara Reservoir storage for Cases A.5(Ave. ann. releases = 10.09 km3/yr), B.5 (Ave. ann. releases =10.47 km3/yr), and C.5 (Ave. ann. releases =9.12 km3/yr).

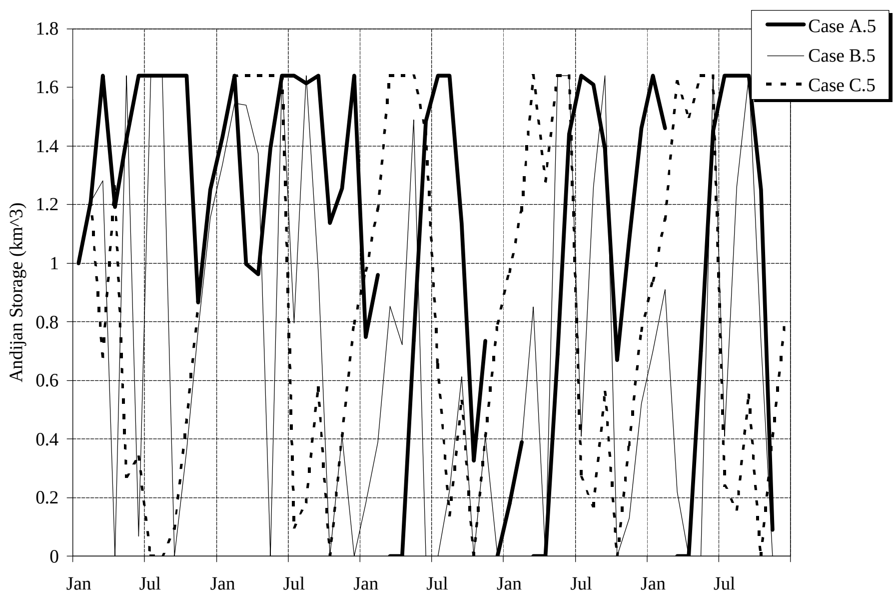

Figure 13. Andijan reservoir storages for Cases A.5, B.5, and C.5.

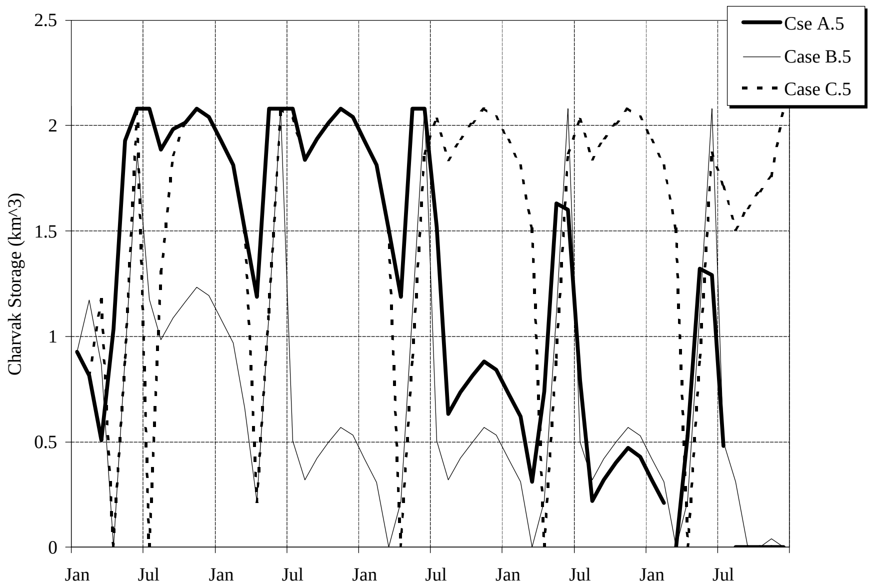

Figure 14. Charvak reservoir releases for Cases A.5, B.5, and C.

Table 9. Spatial Distribution of Water Supply Deficit for Three Cases.

Water Deficit	Lower Syrdarya	Artur	Chakir	Middle Syrdarya	Naryn	Fergana	Total
Case A	0.00	2.80	1.26	0.00	0.00	5.46	9.52
Case B	0.00	3.07	1.38	0.00	0.88	5.39	10.71
Case C	0.90	4.22	1.58	2.95	1.89	0.79	12.32

Estimates of the values of water in certain capacities in the Aral Sea basin have been made (Anderson, 1997; and Burns and Roe, 1996) for hydropower, irrigation, and the Aral Sea. These estimates are highly uncertain and make no allowance for variations in soil productivity, additional inputs, or possible water conservation measures. Water values are shown in Table 10.

Table 10. Benefits and costs of various water uses in the Syrdarya basin.

Use		Benefit	Cost
Hydropower	($/kWh)	0.01 [a]	0.01 [a]
Irrigation	($/km3)	0.038 [b]	0.003 [a]
Aral Sea	($/km3)	0.0375 [a]	0.0

a. Anderson, 1997
b. Burns and Roe, 1996

Case A (irrigation) provides the most water to the agricultural sector and the greatest net benefits of the three scenarios. The 9.05 km^3 annual average agricultural water deficit is shared between the Artur, Chakir and Fergana demand areas. The 1885 GWh annual average power deficit occurs in December - April and power surplus' occur during May - November.

Case B (irrigation + power) results in a 10.7 km^3/year agricultural water deficit, which is 1.2 km^3/year greater than Case A. The water deficit is shared between the Artur, Chakir, Fergana, and Naryn demand areas. There are no power deficits under this scenario. The reservoirs of the Syrdarya basin are operated in an integrated fashion to capture and store water released from Toktogul for power generation in the winter period for later release for agricultural production. It should be noted that it may be possible to offset the increase in agricultural water deficit by increases in irrigation system efficiencies.

Case C (power) provides the greatest power generation, 9657 GWh/year. However, when compared to Case B, this comes at the expense of a 1.64 km^3/year increase in agricultural water deficit. The water deficit is now shared between all the demand areas.

Table 10. Results of Three Modeled Scenarios (9.33 km3/yr flow to Aral Sea).

Use		**Benefits**			**Costs**			**Net Benefits**
		Price	Quantity	Value	Cost	Quantity	Value	
		$		10^6 $	$		10^6 $	10^6 $
Case A (Irrigation)								
Hydropower	(GWh)	0.01	8,927	89	0.01	1948	19	70
Agriculture	(km3)	0.038	34.3	1,302	0.003	34.3	103	1,199
Aral Sea	(km3)	0.0375	9.33	350				350
Total	**($)**							**1,619**
Case B (Irrigation+Power)								
Hydropower	(GWh)	0.01	9,108	91	0.01	0.0	0	91
Agriculture	(km3)	0.038	33.1	1,258	0.003	33.1	99	1,159
Aral Sea	(km3)	0.0375	9.33	350				350
Total	**($)**							**1,599**
Case C (Power)								
Hydropower	(GWh)	0.01	9,657	97	0.01	0.0	0	97
Agriculture	(km3)	0.038	31.4	1,193	0.003	31.4	94	1,099
Aral Sea	(km3)	0.0375	9.33	350				350
Total	**($)**							**1,545**

Conclusions

The objective of the work described here is to aid the countries of the Syrdarya River basin to develop a long-term water and hydroelectric power sharing agreement. As part of these activities a policy analysis tool has been developed to help decision makers from the Syrdarya basin republics come to an agreement for the allocation of water releases from Toktogul reservoir on the Syrdarya River. This multicriteria decision analysis tool can be used to promote an understanding of the tradeoffs between water releases made for agricultural production and those made for hydroelectric power generation. This multi-objective screening model may aid in the determination of fair and equitable arrangements for sharing the waters of the Syrdarya River between the CAR countries of Kyrgistan, Uzbekistan, Kazakstan, and Tajikistan. Such a model may prove to be useful in assisting CAR decision makers in negotiating agreements or treaties between the countries of Kyrgistan, Uzbekistan, Kazakstan and Tajikistan over the distribution of releases from the reservoir.

The major constraints related to this work include:

- **Data limitations.** The model reported here has been developed with a bare minimum of up-to-date data on the system physical properties and operation, and this minimizes the usability of the results at this time. This information is not available outside of the local region and gaining access to it requires close cooperation and contact with local officials.

- **Simplifying assumptions.** The model reported here was developed with certain simplifying assumptions. Such as the treatment of groundwater aquifers and the lack of consideration of salinity. Given additional time and resources, much more detailed and accurate calculations could be performed.

- **Local capacity.** The ability of local officials to understand and accept the decision analysis tool developed here is unknown at this time. It is unclear what current methods are used to compute projected releases from Toktogul reservoir.

If the countries of the Syrdarya basin are interested in finding a resolution to their mutual problems, they may even be willing to accept some increased expense in order to reach an agreement that avoids catastrophic conflict and economic hardship in the future. However, at the present time, the Kyrgyz have instituted charges to Uzbekistan and Kazakstan for all waters released from Kyrgyz reservoirs.

The Kyrgyz operation of Toktogul reservoir in a winter power production mode (Case C) with little or no consultation of the downstream countries may leave the downstream countries, Uzbekistan and Kazakstan, with no assurance that Toktogul reservoir will have adequate storage for summertime irrigation releases. Thus, these countries strive to keep the downstream reservoirs, Kayrakum and Chardara, as full as possible during the winter, resulting in flooding and diversion into the saline Arnasai depression when large winter releases are made from Toktogul.

Given the existing situation and the results of the irrigation + power scenario (Case B) presented above, it seems necessary to provide some means of allowing wintertime releases of water from Toktogul reservoir to satisfy Kyrgyz winter power demand. In order for this to be successful, the downstream reservoirs must be operated in an integrated fashion with Toktogul in order to capture wintertime releases and store them for summer release. In other words, all of the water resource facilities of the Syrdarya basin must be operated in an integrated manner to reduce conflict in the basin and to provide the maximum net benefits to the countries of the basin.

Current methods of calculation of the releases from Toktogul reservoir do not consider the costs and benefits resulting from these releases. The model developed here forms the basin for performing these economic calculations and represents the standard international practice of performing such calculations. This model may be viewed as one alternative for performing these type of analyses.

Price and cost information relevant to the model was developed during the recent visit to Almaty. However, this information was only applied to the output from the model. In order to truly see the impact of economic instruments (prices and costs) on the allocation of water in the basin, the model must be revised so that these factors are internal to the model.

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