World Academy of Science, Engineering and Technology
International Journal of Mathematical and Computational Sciences
Vol:3, No:5, 2009

Conflicts and Compromise at the Management of Transboundry Water Resources (The Case of the Central Asia)

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***Abstract*—**The problem of complex use of water resources in Central Asia by taking into consideration the sovereignty of the states and increasing demand on use of water for economic aspects are considered. Complex program with appropriate mathematical software intended for calculation of possible variants of using the Amudarya up-stream water resources according to satisfaction of incompatible requirements of the national economics in irrigation and energy generation is proposed.

***Keywords*—**water resources, national economics, irrigation, transboundry, energy generation, optimal solution, program complex, up-stream, down-stream, compensating services.

I. Introduction

PROBLEM of joint management of transboundry water resources and energy generation for Central-Asian republics are main factors, which defined practically all aspects of the national and regional economics.

Up to the recent time the Central-Asian republics have exploited their water resource systems within the distributive scheme. This scheme considered the region as a space controlled and guided by the center. Former mechanism of centralized management of the water recourses provided reliable work of all hydro technical constructions coordinating solutions of problems on regional water using within multiyear regulation of river flow. This mechanism has been guaranteed for stable function of agricultural sector based on irrigation and safety flow of water to river downstream during winter-spring period. Each republic supported the rational balance between energetic and other resources, which contribute for regulation of delivery the energy supply and appropriate distribution of water recourses between republics.

However, presently the political and economic situation in the region has radically been changed. After proclamation of independence, each of the sovereign state tends first of all to maximize the use of all natural resources, taking into account the own economic and political interests.

Thus, the main water potential of Central Asia is concentrated in the basin of two big rivers the Syrdarya and the Amudarya which provide needs of population of five countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan). The interrelation of the countries in the region depends on true choosing of water resources management strategies.

There are certain disagreements between the states of the Amudarya and the Syrdarya transboundary upstream and dounstream river basin according to energy potentials in up-stream rivers. As an example, Kyrgyzstan completely determines the policy of use the Syrdarya basin water resources being formed in its territory. Other Central-Asian republics, using water resources of the Syrdarya river, are compelled to be satisfied with it. Such the situation has initiated the introduction of compensating services between the republics of the region.

However, the certain interstate arrangements are not undertaken than the finalizing construction of the big hydropower stations which started in 80th years (Cambaratin in Kyrghyzstan, Sangtuda and Rogun hydroelectric power station in Tadjikistan) can change essentially a regim of Syrdarya and Amudarya river which they had been earlier.

Situation in the Amudarya river basin can become more aggravated, if we take into account Afghanistan intentions in the near future to act with requirements on participation in water distribution in Pyandj river basin. As a result the volume of water will be reduced for Turkmenistan and Uzbekistan especially in the Amudarya basin downstream.

The main problems existing between Central-Asian republics in the field of water and energy regulation are:

1) contradictions between interests of the states which are in upstream and downstream of the river;
2) absence of interstate structures in sphere of a joint management of the water-energy resources, allocated corresponding authorities;
3) recommendatory character of making decisions and absence of any responsibility for their execution at the level of the created regional management structures;
4) inconsistency of actions at regional and national levels between management structures of water economic and power engineering;
5) absence of arbitration practice between countries which have conflict concerning distribution of water resources with opportunities of real influence to the solution of this problem.

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II. Problem Solution

For decision of these problems it is important to take into consideration of the realizations of the following main positions:

- formation of the coordinated regional policy of fair and reasonable development and use of water-energy resources based on international law with participation of all countries of the region;
- complex assimilation of hydropower energy potential and regulation of water and energy resources and maintenance synchronism of their decisions;
- production of effective economical and legal mechanisms of co-operation which are guaranteed caring out accepted decision;
- working out the complex of mathematical models of the accepted decisions, allowing modeling various scenario of water using in the basin of transboundry river.

Proceeding from this in 1992 Institute of Mathematics of Tajik Academy of Sciences brought in Tajik Government the proposal on developing a substantiated strategy to using the Vakhsh river water resources. That proposal was taken and a series of governmental institutions was associated to realizing the project suggested. Institute of Mathematics prepared the computing complex intended for calculation of possible variants to using the Vakhsh river water resources with regard for satisfaction of incompatible requirements of the national economics in irrigation and power engineering. The first computing experiences were completed [1]. But the civil war that enveloped Tajikistan for a long time interrupted the elaboration of the water strategy for our Republic.

The terminal aim presupposed to be achieved at the process of developing the problem is contained in forming the state strategy to a rational use of the Amudary basin up-stream Central-Asian republics. Principal aspects of the strategy should be brought to the information of other Central-Asian republics in order to conclude an interstate agreement on using the Amudary river water resources. In this connection the problem of a complex use of the Central Asia water resources will be completely decided by taking into consideration the sovereignty of the states and their market interrelations.

The project suggested by author is directed to achieving the purpose mentioned. While realizing the project the following results will be obtained:

- the computer instrumentality for conducting the calculation such as to get acceptable variants of utilizing the Amudarya basin up-stream water resources by managing the activity of the reservoirs cascade existing;
- the computer instrumentality for conducting an analogous multi-variant calculation in case the Rogun's reservoir is constructed and joined to the reservoirs cascade for a combined regulation.

The instrumentality will allow:

- to carry out an expert selection of reasonable variants to using the water resources;
- to develop recommendations for the Tajik Government to realizing the new water use policy.

To get the mentioned results the following actions are planned:

- gathering, systematizing and integrating the hydrologic, hydro-geological and morphometric data on the Amudary basin up-stream and existing modes of the hydrounits ;
- creating a database of the information;
- qualitative and quantitative estimations of the Amudarya up-stream water resources, i.e. the water resources of the Vakhsh river;
- developing the program complex for management of the Vakhsh cascade with regard to priority of the Tajik Republic requirement in electricity (in two variants: both for the existing cascade of reservoirs and for the cascade extended by the Rogun's reservoir);
- realization of computing experiments for a qualitative estimation of efficiency of different managing decisions to functioning the Vakhsh cascade of reservoirs;

creating information system of the Amudary transboundry river with using of the Geographical Information System (GIS).

III. Mathematical Software

Three levels of mathematical models are offered: *analytical, optimization and imitational*. Within the framework of analytical models [2],[3] the theoretical-game models of distribution of water resources between the states of the Amudary basin are considered. A number of characteristic examples of games with not opposite interests concerning to problem of rational use of water resources of the transboundry basin are discussed [4].

Water-division problem for the transboundry basin is spent from the point of view of the system analysis and a model of substantiations of cooperation of countries-users of water resources of the transboundry river is offered. Suggested approach is focused on research of efficiency of cooperation at management of water resources on a qualitative level.

For a finding effective (optimum on Pareto) ways of water distribution the following procedure is offered. On all managements of all countries and the prices p^k are a maximum of expression

$$\sum_{k=1}^{n} \max_{A_u^k, A_d^k} \mathrm{M} \max_{w_b^k, w_w^k, w_a^k, c_u^k, c_d^k} g^k$$

where M - operator of calculation of a mathematical expectation designates; A_u^k, A_d^k - appropriately area borrowed under agricultural crops and located above and below a reservoir in country k; w_b^k, w_w^k, and w_a^k - appropriately outflow from reservoir of country k before, during and after irrigation period; c_u^k, c_d^k - appropriately volume of water, used for irrigation from source of country k in the up-stream and down-steam of reservoir.

Let's consider, that the purposes of the countries k are described by the following auxiliary criteria: agricultural production $C^k = C_u^k + C_d^k$, and $C_d^k = \psi^k(A_d^k, c_d^k)$ - the production functions (during vegetation water collects, then it is used by optimum ways for agricultural productions); $e_b^k = \varphi^k(w_b^k)$, $e_w^k = \psi^k(w_w^k)$, $e_a^k = \varphi^k(w_a^k)$ - volumes of the electric power generations is determined by production functions; $W_a^k = W_b^k + w^k + w_o^k - c_u^k - w_b^k - w_w^k - w_a^k$ - probability of state of emergency as a result of a drought in the future which monotonously depends on a stock of water; W_b^k - stock of water in reservoir by the beginning of a year; $f^k = p_e^k(e_b^k + e_w^k + e_a^k) + p_c^k C^k$ - financial expenses; p_e^k, p_c^k - appropriately of monetary expenses for production of unit of the electric power and production of unit of agricultural products in country k; $m^{k+1} - m^k$ - benefit from sale of water.

Let's accept restrictions on a choice of managements in the form of likelihood restrictions that provides a level of guaranteed feedback of water object: $Bep(c_u \le w_u + w_o, c_d \le w_w) \ge b$, where the level b characterizes a guarantee for which the managing body of the country expects. We fix the following mechanism of water calculations. We shall consider that for volume of water w^k, corresponding to a point status quo, the country pays nothing, and water over this quantity gets under the price p^k. Decision-making is based on use of convolution of criteria $g^k(C^k, e_b^k, e_w^k, e_a^k, W_a^k, f^k, m^{k+1} - m^k)$. It is proved

Theorem 1. Let in a point status quo inequalities

$$\frac{\dfrac{\partial g^{k+1}}{\partial C^{k+1}} \cdot \dfrac{\partial \Psi^{k+1}}{\partial c_d^{k+1}} + \dfrac{\partial g^{k+1}}{\partial e_w^{k+1}} \cdot \dfrac{\partial \psi^{k+1}}{\partial c_d^{k+1}}}{\dfrac{\partial g^{k+1}}{\partial m^{k+1}}} > \frac{\dfrac{\partial g^k}{\partial C^k} \cdot \dfrac{\partial \Psi^k}{\partial c_d^k}}{\dfrac{\partial g^k}{\partial m^k}}$$

are execute for all k. Then the point status quo is not effective.

On the basis of the theorem, on an induction, since $t=T$ and finishing $t=1$, it is checked, that on each step of the algorithms described in a dynamic case solve the problems completely similar to problems, considered at the analysis of static models. Therefore all qualitative conclusions received earlier concerning efficiency of association of the countries in a coalition and opportunities of improvement of position of the countries in comparison with a condition status quo, are kept and in a dynamic case. A determinative is the opportunity of use by down-stream countries "benevolent" of outflows of up-stream countries, and also an opportunity of direct exchanges of the goods and resources without monetary calculations. Certainly, the effect from cooperation will collect year by year.

For a case when the considered river has inflows and in each country there are some power stations, all received qualitative conclusions concerning effect of association in a coalition and expediency of cooperation are kept. As well as in the linear cascade is a condition status quo. For this purpose it is necessary to solve some problems of optimization consistently. We shall record on the considered river one point in a month and one point in a source. We shall allocate on the unique simple way connecting these points on one power station in territory of each country. The managements concerning to all other power stations and adjoining it agricultural land, we shall put equal to corresponding values in a point status quo and we shall record. By virtue of the established properties, there will be managements which give all players prizes big, than in a point status quo. If we now "shall release" earlier fixed managements prizes of all players can increase only.

Optimization models [2] of the reservoir management of the Amudary up-stream water resources are offered which put as a base the "block-hierarchical" principle which provide at the initial stage development of different national models and their further coordination within the framework of regional models. According to it we can divide territory of the Amudarya basin into two zones accordingly: *formation zones of demand and offer of water*. Hierarchical tasks of management of reservoirs are considered which provide the aggregated needs of the states in the demand zone on irrigation when the hydroelectric power limitation is carried out.

Let the transboundry basin is divided into two zones - a zone of formation of water resources and a zone of their consumption. In a zone of formation reservoir of long-term regulation, and in a zone of consumption - reservoir of seasonal regulation functions. Hierarchical problems of management of reservoir which provide the aggregated requirements of the states of a zone of consumption on irrigated agriculture, under condition of performance of restrictions on production of the hydroelectric power are considered.

Management is function $u^k(t)$ actual outflow from reservoir at the moment of a season t a year k for long-term rows $\{n \times T\}$ where n - set of the years numbered by an index $k = 1, 2, \ldots, n$. Every year consist of T intervals with the current index t, $t = \overline{1, T}$. Let $w^k(t)$ - required outflow water at the moment of t a year k, necessary for satisfaction of requirements of irrigated agriculture. Production of the electric power at the moment of t a year k, is designated through $E^k(t)$.

The problem consists in an optimum choice of management $u^k(t)$ which delivers the minimal or maximal value of criteria function:

$$I_{irr} = \sum_{k=1}^{n} \sum_{t=1}^{T} (u^k(t) - w^k(t))^2 \tag{1}$$

$$I_{elec} = \sum_{k=1}^{n} \sum_{t=1}^{T} E^k(t) \tag{2}$$

Dynamics of a condition of reservoir is described by the ordinary differential equation

$$\frac{dx^k(t)}{dt} = v^k(t) - u^k(t) \quad (3)$$

in area $v^k(t) \geq 0$, $u^k(t) \geq 0$. (4)

Where $x^k(t), v^k(t)$ - appropriately a condition of reservoir and inflow of water to reservoir at the moment t a year k.

It is considered set initial volume of water in reservoir

$$x^1(0) = x^0,\ x^{k+1}(0) = x^k(T),\ k = \overline{1, n-1} \quad (5)$$

and also restrictions are carried out

$$x^- \leq x^k(t) \leq x^+, \quad (6)$$

where x^- and x^+ - accordingly minimally and as much as possible allowable volumes of water in reservoir, and

$$\sum_{k=1}^{n}\sum_{t=1}^{T} H(\overline{x}^k(t), u^k(t) \cdot u^k(t) \cdot \eta \geq E^k(t), \quad (7)$$

where $H(\circ,\circ)$ - a pressure of the hydroelectric power station, monotonously growing function on $\overline{x}^k(t) = \frac{x^k(t+1) + x^k(t)}{2}$ and monotonously decreasing function on $u^k(t)$; η - the set factor determining efficiency of hydroelectric power station.

Thus, we have the problem of mathematical programming consisting in minimization (1) and (or) maximization of criterion function (2) at restrictions (3) - (7).

The technique of finding a compromise solution among needs of the states in volumes of consuming water at the level of the coordination of management between zones of consumption and formation is offered. It is shown, that for countries which are in different geographical zones it is different both schemes of constructions of models and their relations to each other. For example, between countries of the offer and demand zones the scheme of compensartion is offered: Uzbekistan and Turkmenistan (demand zone), getting necessary water during the vegetative period simultaneously accepts the electric generated in Tajikistan (offer zone). During winter period Uzbekistan and Turkmenistan return received electricity or volumes of other its equivalents power to the offers zone as well.

Construction of imitational models is carried out on example the Vakhsh-Amudarya cascade of reservoirs [1],[3]. The cascade includes three large reservoirs, such as Rogun, Nurek and Tuymuyn. Mean while, these reservoirs are located in the territory of different Central-Asian republics, namely: Rogun and Nurek belong to Tajikistan and Tuymuyn to Uzbekistan.

Tajikistan being in the zone of drain formation of the Amudarya river basin can recustomize the main operating rules of reservoir from irrigational to energy regime. We know that Kyrgyzstan carries out such policy concerning to Toktogul reservoir for the last years.

However the compromise variant is offered when satisfaction Uzbekistan requirement on irrigation calculates beforehand based on imitational models. Production of hydroelectric power for the Vakhsh cascade to calculates in parallel, which will be getting according to irrigation regime. Recalculation of the not received generation of the electric energy is carried out. This volume of unworking out energy should be compensated by the countries of the Amudarya down-stream water resources.

Within the framework of imitating model, are offered a technique of the automated construction of dispatching rules of management by the linear cascade of reservoir of complex purpose.

The problem of management by the linear cascade from three reservoirs located on transboundry basin is considered. It is supposed, that the cascade is intended for maintenance with water of the agricultural production located between the second and third reservoir and is lower than the third reservoir, and also for development of the electric power in two top hydrounits.

Criterion of management for irrigated agriculture is the satisfaction of requirements on number of uninterrupted intervals, i.e. at calculation on a line of supervision for an estimation of security the share of intervals in which corresponding requirements were satisfied is accepted. As a criterion of management on production of the electric power to accept a level of guaranteed monthly average total capacity which it is necessary to support hydroelectric power station of the cascade within a year. Managing parameters are volumes outflow from the up-stream reservoir (outflow from the third reservoir it is unequivocally determined by requirements of irrigation).

Lexicographic ordering problems is considered, i.e. needs of an agriculture first of all are satisfied and only at performance of this condition the problem about hobby of production of the electric power is solved.

At the decision of an irrigational problem joint functioning first two reservoirs of the cascade is considered. Dispatching schedules are under construction counting upon total volume of water in these reservoirs. It is proved by that, first, there is no top restriction on outflow from the first reservoir; second, in model time going is not taken into account, i.e. dynamic components of capacities of water basins and, thirdly, in down-stream the first reservoir are absent irrigational requirements.

Let's designate through $\overset{=k}{u_l}(t)$, $l = 1,2,$ accordingly full and reduced irrigational norm of feedback in k year for an interval of time t in down-stream of the incorporated reservoir. Then dynamics of a condition of the incorporated reservoir is described by the following balance ratios:

$$x^k(t+1) = x^k(t) + v^k(t) - u^k(t) \quad (8)$$

$$\begin{cases} x^k(t) = x_1^k(t) + x_2^k(t) \\ v^k(t) = v_1^k(t) + v_2^k(t) \\ u^k(t) = u_2^k(t), \quad t = 1,2,...,T, \quad k = 1,2,...,n \end{cases} \quad (9)$$

$$\begin{cases} x^{k+1}(1) = x^k(T+1), \quad k = 1,2,...,n-1 \\ x^1(1) = x^+ \\ v^k(t) \geq 0, \quad u^k(t) \geq 0, \quad t = 1,2,...,T, \quad k = 1,2,...,n \end{cases} \quad (10)$$

$$x^- \le x^k(t) \le x^+ \quad (11)$$

Where $x^k(t)$ - filling of i reservoir to the beginning of an interval *t* year *k*; $v^k(t)$ - inflow of water to *i* reservoir for an interval *t* year *k*; $u^k(t)$ - outflow (feedback) of water from *i* reservoir for an interval *t* in year *k*;

Formal procedure of finding of dispatching lines $d_1(t)$ and $d_2(t)$ for the incorporated reservoir described by balance ratio (8) - (11) is offered. As the first dispatcher it is considered top bending around so-called curves of sufficient filling of reservoir, constructed for each year from rows. Curves of sufficient filling are under construction (a course back) with feedback $u^k(t) = \overset{=}{u}{}_1^k(t)$ at for the set rows $\{v^k(t),\ t = \overline{1,T},\ k = \overline{1,n}\}$ according to balance ratio (8) - (11) under the formula

$$\tilde{x}^k(t) = \max\left(x^-,\ \tilde{x}^k(t+1) - v^k(t) + \bar{u}_1^k(t)\right). \quad (12)$$

Further at infringement restriction $\tilde{x}^k(t) \le x^+$ the trajectory is modified and $d_1(t)$ defined as

$$d_1(t) = \max_{k\in\{1,2,\dots,n\}} \tilde{x}^k(t), \quad t = \overline{1,T} \quad (13)$$

The second dispatching line is defined as top bending around lines of switching from full feedback on reduced that is as follows. Proceeding from already constructed curves of sufficient filling, the trajectory $\bar{x}^k(t)$ (a course back) with feedback $u^k(t) \ge \overset{=}{u}{}_2^k(t)$ is under construction at $\bar{x}^n(T+1) = x^-$ for rows $v^k(t),\ t = \overline{1,T},\ k = \overline{1,n}$ under the formula

$$\bar{x}^k(t) = \max\left(x^-,\quad \bar{x}^k(t+1) - v^k(t) + \overset{=}{u}{}_2^k(t)\right)$$

Than $d_2(t)$ defined as

$$d_2(t) = \max_{k\in\{1,2,\dots,n\}} \tilde{x}_*^k(t), \quad t = 1,2,\dots,T \quad (14)$$

where

$$\tilde{x}_*^k(t) = \begin{cases} \bar{x}^k(t), & \text{если } \bar{x}^k(t) > \tilde{x}^k(t) \\ x^-, & \text{если } \bar{x}^k(t) \le \tilde{x}^k(t) \end{cases}$$

The case when for some interval *t* value $d_1(t)$ appears less, than value $d_2(t)$ is theoretically possible. In this case it is necessary to increase corresponding values $d_1(t)$ up to $d_2(t)$. It is proved

Theorem 2. *For resolvability of an irrigational problem (problem A) it is necessary and enough that at anyone t and k the inequality was carried out*

$$\bar{x}^k(t) \le x^+, \quad \forall t,k$$

Theorem 3. *The offered technique of construction of dispatching lines* $d_1(t)$ *and* $d_2(t)$, *at performance of conditions of the theorem 2, guarantees performance of an inequality*

$$u^k(t) \ge \overset{=}{u}{}_2^k(t)$$

for all hydrological rows.

Results of the carried out calculations show, that the offered technique of construction of dispatching rules allows to find quickly enough practically comprehensible estimations of an opportunity of satisfaction of incompatible requirements of the national economics in irrigation and energy generation.

IV. Decision-Making

Program realization of mathematical models, data base, ways of reception and transfer information, method of organization dialogue with users, visualization means based on GIS are decision-making support system (DMSS). Methodology of creation of the DMSS includes questions: *computer modeling of managing decision-making*; solving *problem of multi-purpose management of water resources; carrying out decision on results of imitation modeling.*

In the structure of methodology of decision problem of multi-purpose management of water resources the original approach proposed to solution complex problem of planning and using water resources of the transboundry basin. The first aspect approach related to spatial division territory of considering basin on levels of management. The second determined by multi-purpose problems related with identifying appropriate compromise solutions between states on using water resources by taking into consideration of economic interests. Combination of multilevel and multidisciplinary goals represents the key moment of methodology offered approach.

The specialized applied program of DMSS uses of program software MS Office operation system Windows XP & GIS Arc Info/Arc View. Information database is constructed based on MS Access and mathematical models are used for finding of optimal solution. Analysis and representation of spatial data is carried out based on GIS technology.

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