4. MULTI-YEAR REGULATION OF SYRDARYA BASIN FLOW

4.1. Models for Designing Multi-Year Regulation of Syrdarya Flow

4.1.1. Introduction

Inflows to the Toktogul, Andijan and Charvak reservoirs, the amount of lateral inflow and water requirements all “dictate” the operation mode of the Naryn-Syrdarya cascade of reservoirs. The planning of the cascade’s long-term operation (over several years) is, above all, the forecasting of reservoir storage. Therefore, the estimation of the operation of the cascade should look several years ahead, and for this period a forecast should be made. The forecast should be based on a long-term prognosis of water resources, it should be an evolved scheme for the current year and a specified program for the next few years. This will provide a greater reliability of each reservoir and the cascade as a whole. The idea of how important this forecast is became evident after the unexpected low-water year of 1995. To some respect, the shortage of water that occurred that year was the result of a lack of forecasting. Another example (having an opposite “sign”) is the vegetation period of 1998, an extremely wet season, notwithstanding the prognoses, which both satisfied all water user demands and increased the Toktogul storage to 15 km^3. At the beginning of that year the reservoir was almost completely empty. The maximum inflow to Andijan Reservoir in June and partially in July and extremely large releases caused excess water to be discharged into the Arnasai depression. If accurate forecasting had been made at that time it would have been possible to draw Andijan Reservoir down beforehand, in the beginning of the vegetation period, and mitigate high water aftereffects.

This is why, the idea in recent years to forecast the situation for a number of future years in order to ensure efficient operation planning of the reservoirs located on the main Central Asian rivers becomes more and more insistent. Methods for long-term water forecasting (1 year and more ahead) are being developed, and, on the basis of these methods, it is necessary to make forecasts of the operation of the cascades on the Amudarya and Syrdarya rivers. Some forecast operation elaborations (for 5-7 years) have already been made for the Naryn-Syrdarya cascade.

This issue should be considered in more detail taking into account the results achieved by the BVO Syrdarya together with the interested agencies. In the future, this kind of study should be continued and extended.

In the first place, a retrospective analysis is needed of hydrologic series related to natural inflows to the three upstream reservoirs of the cascade and lateral inflow to the Syrdarya channel and its main tributaries, Chirchik and Karadarya. Such an analysis will illustrate the shape of the cycle. The characteristics of the analyzed parameters will serve as a basis and will help to extrapolate the investigated phenomena and give an approximate water prognosis for years ahead.

4.1.2. Present stage

At present, at least two approaches for the development of long-term forecasts that have been used by the BVO Syrdarya. The general approach to the methods is that very often it is necessary to know the future status of certain facilities or systems, including natural systems. In other words, a forecast of their dynamics is needed well in advance. While developing forecast methods, investigators face three important problems: (1) what characteristics may be considered as predictors, (2) where should they be sampled and estimated spatially, and (3) at what times should they be sampled and estimated. There is not yet any formalized algorithm answering these questions. We should rely on the observations of previous years and take into account that the investigated phenomena are primarily accidental (stochastic).

Consider the long-term forecast methods that will allow us to identify the future size of the natural inflow to the Syrdarya reservoirs with multi-year storage. They will help to conduct investigations based on the size of natural inflow. Other methods may be used to define lateral inflow to the Syrdarya for the same period, and at each river site the value of lateral inflow should be tied to peculiar features of inflow formation and abundance.

First approach

The first method of long-term forecast to identify the natural inflow to the upstream reservoirs of the Naryn-Syrdarya cascade is based on projecting a climatic trend and its deviations on the one hand, considering the series of annual average air temperature of the northern hemisphere, and on the other hand, it is based on annual recurrences of Van Gengeim-Girs atmospheric circulation with its forms C and M2. For each climatic element we identify complex trends and use the model of cyclic components. A complex 70-year climatic trend consists of a linear trend and harmonics. The data on variation of air temperature are taken from Jones' paper, and annual recurrences of circulation forms C and M2 are singled out based on the series of observation. As the inflow series are much shorter than the series of global climate change characteristics, we, when marking out complex trends of hydrologic series, use the period values received from the series of average air temperature and C and M2 recurrences (70-year periods). The singled out trends are statistically important. Similar statistically important trends are also chosen within the series of annual recurrences of synoptic processes of Central Asia and this is an indicator of interlinks of regional atmospheric circulation and river flows from the formation zone. The climatic trends of the inflows to Toktogul, Andijan and Charvak reservoirs are forecasted through extrapolation. We average the climatic trend deviations and with the help of average values we forecast trend deviations. The final forecast is calculated by adding trend deviation forecast to extrapolated climatic trend value.

The developed method forecasts reservoir inflow for 1-7 years, the most successful prognoses occur when we forecast from 2 to 6 years ahead, and this confirms the hypothesis of a quasi-two-year cycle and 6-7-year periodicity. For the vegetation period, the 6-7 year Toktogul forecasting justified itself by 70%, if we keep in mind the admissible error, for Andijan Reservoir it is also 70%, and for Charvak Reservoir it is 80%. For a one year period these figures are 75%, 78% and 78%, respectively. The forecast justification was calculated based on 1980-90 data. A computer program has been developed for the method and it was realized as a software product.

Second approach

The second approach to multi-year forecasting differs from the first approach as described in the following. Average annual water discharges (*Q*) at the forecasted site, annual basin precipitation at a certain elevation and the basin average air temperature at the same elevation are used in this method. The forecast is based on the method of multiple regression, but differing from the existing approach (where the prognosis is given only for half a year, vegetation or non-vegetation period) in that it uses the time (years) preceding the forecast, and the predictor values are included in the time values. The algorithm of the second method is based on an optimal combination of components (number of terms of the series taken from the forecast point), predictors, and the minimized function denoting deviation of the design value from the measured value.

Based on this method, monthly inflow to Toktogul, Andijan and Charvak reservoirs are calculated, and for the same time we compute lateral inflow to the Syrdarya, Karadarya and Chirchik channels. For this we use multi-year series of average annual water discharges, average annual air temperature and annual precipitation values registered by weather stations located in the Naryn, Karadarya and Chirchik basins. The method was verified for 1987-97. The estimations justifying the forecasts demonstrate the method's serviceability for long-term hydrologic prognoses. Nevertheless, the method requires a more accurate selection of predictors and more correct forecast estimation. It is also necessary to expand the source flow information base, which serves as a basis for the forecasting.

4.1.3. Next stage

The next stage will be allow forecasting more precise marginal conditions of operation of the upstream reservoirs (Toktogul, Andijan and Charvak) and seasonal channel reservoirs (Kairakum, and Chardara) of the Naryn-Syrdarya cascade. For forecasting the cascade operation, compliance with these conditions will promote normal functioning of the reservoirs, hydro-control and other hydraulic structures of the water management complex. It will also assist in maintaining optimum environmental conditions in the areas adjacent to the reservoirs and in the basin on the whole, in providing a normal water diversion regime and in continuous functioning of pump stations that take water directly from the Kairakum Reservoir. Flow limitations, channel carrying capacity within the site considered, sanitary flows should be also referred to marginal conditions. All constraints are tied to the technical characteristics of the facilities, technical and other specific conditions under which the facilities operate. For instance, the Syrdarya (Upper, Middle and Lower Syrdarya) sanitary flows were set for the time when the population of the Syrdarya Basin was 2-3 times less than the current population. Naturally, changes should be taken into consideration when specifying the starting conditions for forecast calculations. It should be noted that some constraints already exist in the BVO Syrdarya, but we should not exclude new constraints and conditions that may occur because of natural, political and economic policy in the Syrdarya Basin.

Tentatively, we may split these constraints into two categories. In the first category we may include so-called general technical (passport) constraints. For example, a reservoir's normal maximum operating level should not be exceeded, and the dead storage must not be used. We will not describe the second category, which refers to a reservoir's specific operating conditions. We will only give one example. For normal operation of the Makhram pump station lifting water from the Kairakum Reservoir, the reservoir's water surface elevation should not drop below 343.5 m (corresponding to 1.716-mln.m^3 storage where 890 mln.m^3 is the dead storage volume, i.e., an extra 1 mlm.m^3 must be kept in storage at all times that the pumping station is in operation). If such conditions are recommended, they are established for forecast calculations only if they are observed in reality, otherwise these constraints are not enforced in the calculations. For example, the constraints recommended for Charvak reservoir (to avoid dust storms in fall and winter, and reservoir filling constraints because of seismic anomaly) are not observed, but the conditions for Kairakum reservoir are observed.

As for sanitary flows, the design materials stipulate the following Syrdarya water discharges to ensure satisfactory ecological and epidemiological conditions of the river basin:

- The sanitary flow from Toktogul Reservoir to Kairakum Reservoir should not be less than 100 m^3/s (see the "Toktogul Operation Rules," Institute *Sredazgiprovodkhlopok,* Tashkent, 1988).
- The sanitary flow from the Farkhad water control structure to Chardara Reservoir should not be less than 100 m^3/s (see "Framework of Water Management Measures for the Syrdarya Basin up to 2000" and "Operation Rules of the Naryn-Syrdarya Cascade of Reservoirs. Main Provisions," Institute *Sredazgiprovodkhlopok,* Tashkent, 1985).
- The sanitary flow from Chardara Reservoir to the Aral Sea should not be less than 93 m^3/s (see the "Toktogul Operation Rules," Institute *Sredazgiprovodkhlopok,* Tashkent, 1988).

Again, a need exists to review and validate the above data and to match them to current conditions.

It is also necessary to give grounds for water diversions from the Naryn and Syrdarya channels and to aprove similar indices for a year of annual normal water availability for the Chirchik and Karadarya. The regime of water diversions from the Naryn and Syrdarya rivers is grounded in the Project "Framework of Complex Use and Protection of Water Resources of the Syrdarya Basin" and in the correctional note of the "Detailed Framework…" which stipulated the irrigation operation mode of the cascade. Winter water demands (water loading and flushing) for the irrigated lands were met successfully and a need to fill the channel reservoirs was also taken into consideration. The Central Asian countries secured for themselves water resources and set binding water limits (12 km^3) for annual normal inflow to Chardara Reservoir. In dry years the inflow may be decreased but the 90% (or about 10 km^3) water-supply amount had to be ensured. The Project stipulated a secured flow of 1.36 km^3/year to the Aral Sea and the delta. According to the Project the Aral Sea problem might be solved due to the partial flow transference from Siberian rivers. We know that in the late 1980's that idea was rejected. Since 1992, the time of formation of newly independent states, the issue of international water sharing was considered and the program initiated. The ICWC set water limits based on the main provisions of the "Framework…". Later, the Aral Sea and the pre-Aral area received the rights of an independent water user. For the Syrdarya, fixed water flows to the Aral Sea ranged from 4 to 6 km^3 with 1-1.5 km^3 during the vegetation period.

As was mentioned, ICWC meetings approve water limits in the beginning of each water year and specify water withdrawal amounts before the vegetation period. In case the situation changes (low or high water seasons) the limits are adjusted after a necessary substantiation.

If the proposed forecast methods are approved, water diversion limits should be fixed based on multi-year forecasting. If the prognoses show a shortage of water, then the limits will be decreased and forecast calculations for the Naryn-Syrdarya cascade operation will compute this decreased amount. There is one more important consideration: during the latest decade the existing water diversion limits do not take into account the changed crop structures in the basin. The analysis of actual water diversions clearly demonstrates that increased non-vegetation water diversions are resulting from the necessity to irrigate winter crops in September-November, especially in Uzbekistan.

4.1.4. Closing stage

Calculations forecasting long-term operation (5-7 years) of the Naryn-Syrdarya cascade of reservoirs is the closing stage of the activities. The calculations should be done for each economic year and they should be based on the above information and the data on initial reservoir conditions.

The multi-year forecasting will indicate the dynamics of the cascade operation, and this will make it possible to take expedient measures in case of threatening tendencies. A precarious situation occurred in the period from 1995 up to the beginning of 1998 when water storage of Toktogul Reservoir was close to dead storage. In addition, the prognosis will allow determination of the operation mode of long-term storage reservoirs, which will promote prevention of such tendencies from the earliest possible time and provide necessary reservoir storage (or release on the threshold of a coming wet season). This operation mode will help to avert dangerous situations (especially, if a cycle of dry years is anticipated).

The forecasted operation regime will be adjusted as soon as specific Hydromet Services' prognoses are available. If the forecasted water resources exceed the norm, then it is possible to set the reservoir storage and increase water delivery to the Aral Sea and pre-Aral zone, fully supplying water users with water. If we have the results of a long-term forecast in the future, we may avert the situations of the recent years when only the abnormal high-water phenomena prevented Toktogul reservoir from full drawdown. Otherwise, Toktogul might lose its main purpose, viz. to regulate the Syrdarya multi-year flow and "validate" the operation of the Naryn-Syrdarya cascade of reservoirs. The results of the forecast calculations will assist in rational operation of other reservoirs of the cascade to secure the most effective water delivery from Chardara to the Aral Sea and pre-Aral area and minimize losses of scarce water resources as happened in the years since 1992, i.e., Chardara discharges to the Arnasai depression.

4.2. Principles of Multi-Year Flow Regulation of the Syrdarya River

4.2.1. Background

When we speak about multi-year regulation of a river basin we mean a complex of measures to partially accumulate flow in wet years and appropriately allocate the resource in the years of low water availability. Facilities implementing that role are called long-term storage reservoirs (LSRs), and the methods (rules) of their filling and drawdown refer to the theory of multi-year regulation. The LSRs may be off-system reservoirs or channel reservoirs attached in a cascade, in this case we talk about cascade flow regulation. Besides a multi-year basin regulation there is seasonal (within-year) flow regulation with the idea of transforming a seasonal hydrograph to meet the needs of water users (e.g., hydropower generation) and water consumers (e.g., irrigation).

The channel LSRs usually participate in both processes, i.e., in multi-year and seasonal regulation. The theory of multi-year flow regulation goes back to water calculations, which rely on mean statistical flow parameters which can be used to identify dependencies among the LSR storages, appropriate water diversions and the percent of the diversion that can be ensured. As a rule, calculations show overestimated economic indices regarding flow regulation, and what is most important, the calculations leave open issues related to decision making under specific conditions.

Water calculations are widely used at the design stages when variants to develop a water management complex are worked out. Further progress of the theory of multi-year regulation is tied with study of occasional (stochastic) processes and modeling methods. Stochastic models in contrast to deterministic models do not work with average flow values, but rather with stochastic parameters, and this helps account for various damaging variants which may emerge when years of different water availability are combined. As a rule, stochastic management models do not provide a definite decision even if we have a single criterion of efficiency. However, the models single out the area for the best decisions and eliminate wittingly ineffective variants. As only the simplest stochastic models may be solved analytically, issues relating to stochastic modeling get entangled, and depending upon the problem a stochastic task is solved either through modeling or is analyzed by stochastic methods. Nevertheless, taking into account the existing tradition to separate these model classes we discuss modeling as an independent section.

4.2.2. Multi-year Regulation Using Models

Models used for solution of the multi-year regulation problems are based on the law of conservation of mass (water) written on the graph (usually a directed graph) that formally describes a water management scheme. In order not to shade the core of the problem we will limit ourselves by the simplest graph that has an inflow, outflow and a reservoir. Let $\{t\}=\{1, 2,...,T\}$ be the period of years for investigating processes of multi-year regulation. Denote inflow, release, reservoir storage and losses by $w_0(t)$, $x(t)$, $w(t)$, $\Delta w(w)$, respectively, then the equation of conservation of water may be written as

$$w(t+1)=w(t)+w_0(t)-x(t)-\Delta w[w(t)] \qquad (4.2.2\text{-}1)$$

Under physical constraints

$$w(t) \le w^{\max}; \quad w(t) \le w^{\min}; \quad \forall t \in \{t\} \tag{4.2.2-2}$$

and technological constraints for releases

$$x(t) > q^{\min}; \quad \forall t \in \{t\} \tag{4.2.2-3}$$

Denote by $\delta x(t) = x(t) - q^{min}$ an amount of water that can be used for downstream water users. $C(t)$ is the profit received from a unit of water resources utilized by water users, and $F(w)$ is the function of efficiency of a water unit usage in the reservoir. $dF(w)/ d(w) > 0$ if the reservoir has a hydropower plant, and $dF(w)/ d(w) < 0$ if the reservoir does not have a hydropower plant. A simple task of multi-year regulation may be formulated as follows: For the given time **{***t***}**, and a flow hydrograph $w_0(t)$, we define values $x(t)$ satisfying equations (1), constraints (2) – (3), and with these values the functional reaches maximum:

$$\aleph = \max \sum_{t \in \{t\}} x(t)[F[w(t)) + C(t)] - [(q^{\min} + \Delta w(w))C(t)] \tag{4.2.2-4}$$

An optimization problem of linear programming emerges. If the functions F and C depend on $x(t)$, then we receive a problem of nonlinear programming. Methods of its solution are sufficiently developed by now and do not cause any difficulties. Having $w(0)$ we receive the vector $x(t)$ that returns the maximum for the functional (4), but strictly corresponds to the specified flow hydrograph $w_0(t)$. In statistical investigations the vector $w_0(t)$ is called a sample event on $\{t\}$. Specifying different values of $w_0(t)$ we receive a family of solutions $\aleph(w_0)$ and $x(w_0)$; analyzing the family we receive a statistical estimation: reservoir operation efficiency, conditions for emerging water deficit, soundness of deficit, and etc. However the issue related to specific releases under specific conditions remains open. In this analysis a primary burden is laid on the correct modeling of hydrologic series. Here we may use direct natural series, analogous series, moving series, Markov chains, etc.

Completing this part we should note that all the estimations give an upper bound on efficiency, as we operate using the best so-called “second guess” method. As for actual solutions they will be always less effective. Stochastic modeling can be used to correct the situation.

4.2.3. Stochastic Models for Multi-year Flow Regulation

The efficient effect of using stochastic modeling for multi-year regulation is conditioned, first of all, by the stochastic nature of a hydrologic flow itself, and all water calculations “rely” on this flow. Stochastic modeling does not rest upon the specific flow values but it rests on the distribution functions. These functions are received as a result of processing specific flow values. The findings are usually expressed in terms of probability distributions (theoretical frequency), i.e., the probability to receive this or that parameter in the form of functions or rules that link parameters with each other. To give a concrete expression to our considerations we link a possible water diversion value with the LSR spatial location. To receive a quantitative estimation related to water diversion from the river basin let us consider a stochastic reservoir drawdown and filling. In order not to complicate our considerations we assume that the basin is regulated by one LSR. Let W_1 be the part of the flow that passes through the LSR, and W_0 be a general flow including the part that does not pass through the LSR. $W_1 \subset W_0$. W_1 and W_0 are random values with the distribution functions $F_1(x)$ and $F_0(x)$, ($F_i(x)=P(W_i < x)$, $i \subset 0,1$). By W^o denote the flow diverted from the basin and consider the LSR drawdown and filling process. The drawdown is implemented if $W_0 < W^o$ and is equal to W^o - W_0; if $W_0 > W^o$ the LSR drawdown does not occur. The expected value of the LSR drawdown may be written out as follows

$$\Delta W = W^0 - \int_0^{W_0} x dF_0(x) - W^0 \int_{W_0}^{\infty} dF_0(x) \tag{4.2-5}$$

The filling process may be implemented if $W_0 > W^o$, and flow is accumulated that passes through the LSR. The functions $f_0(F)$ and $f_1(F)$, are the inverses of functions $F_0(x)$ and $F_1(x)$, correspondingly. Denote W^{max} as the LSR maximum storage. Then the LSR filling process may be described by the following function

$$Y(x) = \begin{cases} 0 & \mathit{if}\ 0 < x < W^0 \\ \min[x - W^0, f_1(F_0(x)), W^{\max}] & f\ W^0 < x < \infty \end{cases} \tag{4.2-6}$$

The expected value of the LSR accumulated storage is

$$\Delta W^+ = \int \min[x - W^0, f_1(F_0(x)), W^{\max}] dF_0(x) \tag{4.2-7}$$

Expression (7) immediately accounts for the fact that the integral of the first element of formula (6) is equal to zero. If we want stable operation of the LSR for many years (there is a possibility for the LSR to be filled), then the inequality should be maintained

$$\Delta W^+ \geq \Delta W^- \tag{4.2-8}$$

Entering expressions for ΔW^+ and ΔW^- in (8) and grouping them with regard to W^o, then after doing some simple alterations receive

$$W^0 \leq \frac{\int\limits_0^{W_0} x dF_0(x) + \int\limits_{W_0}^{\infty} \min[x - W^0, f_1(F_0(x)), W^{\max}] dF_0(x)}{\int\limits_0^{W_0} dF_0(x)} \qquad (4.2\text{-}9)$$

The equal sign in expression (9) gives the marginal water diversion value, this value may be required from any river basin. This value may be called the marginal natural and technological basin capacity.

Now, make a quantitative assessment of the reservoir intensive regime. Let W^{mp} be a flow amount required by all basin participants; by k we denote the flow-use repeatability factor ($0 \leq k \leq 1$), and by W^p we denote total basin losses (as flow losses may be a flow function, W^p is a expected loss value). Then, the condition for the reservoir intensive operation may be written as follows

$$W^0 \begin{cases} > W^{TP}(1-k)) + W^P & \text{if not intensive} \\ \leq W^{TP}(1-k)) + W^P & \text{if intensive} \end{cases} \qquad (4.2\text{-}10)$$

Thus, the intensive operation regime of the basin assumes an annual average water deficit equal to

$$D = W^{TP}(1-k) + W^P - W^0 \qquad (4.2\text{-}11)$$

Further, we will consider situations where $D > 0$, as for the river basins where $D < 0$ the task of LSR drawdown is not a primary task. Tasks regarding flood control may be the most likely in this case. Let W_r be the LSR water storage this year and W^M be a theoretical annual average storage in the reservoir. This storage is established at the LSR design stage. According to W^M and $z(W^M)$ (z is the water elevation in the LSR), we choose equipment for a hydropower plant, establish secured releases, etc. The value W^M should be regarded only as an expected value for filling the reservoir and this filling is optimal, otherwise design works are useless.

Requirement 1.

To cover current water deficit a decision should be taken that satisfies the following condition

$$\underset{r \to \infty}{Lim}\, M[D_r] = D, \qquad if \qquad M[D_r] < D \ \forall r \qquad (4.2\text{-}12)$$

Requirement 2.

In releasing or storing water during the current year, decisions should be made to

$$\lim_{r \to \infty} M[W_r] = W^M \tag{4.2-13}$$

Here: $M[D_r]$ and $M[W_r]$ are the expectations of actual shortage and actual filling of the LSR respectively.

The first requirement distinguishes the area in the solution space where an optimum may exist. Violating this requirement will lead to gradual emptying of LSR under any economic criteria. The second requirement reflects mainly the interests of the energy industry and may become a source of conflict between energy and irrigation water uses. This source of conflict is strongly expressed in river basins where the amplitude of integral deviations from the average is very high. These two requirements enable us to formulate the following task defining an optimal strategy for the LSR. Let $\{r=1,2,\ldots,R\}$ be the period of years for which the study of the water management strategy is carried out. Define W_0^r as the annual flow in the basin the year r. By $\varphi(W_0^r)$ denote the part of flow going through LSR (if the correlation coefficient between the flow in the LSR section and the flow in the basin is close to one, then we can consider $\varphi(W_0^r)$ to be a determined function of a random variable. Otherwise, we can define it as a random function of a random argument. The equation of mass conservation written for the basin with regard to (11) gives

$$D^r = \begin{cases} W^0 - W_0^r - \Delta W_r & if\ W^0 > W_0^r + \Delta W_r \\ 0 & if\ W^0 < W_0^r + \Delta W_r \end{cases} \tag{4.2-14}$$

Here: D^r is the shortage of water in the year r, ΔW_r is the release from the LSR in year r ($\Delta W_r > 0$ = drawdown of the LSR, $\Delta W_r < 0$ = filling of the LSR).

From an analogous equation written for the LSR we have

$$W_{r+1} \le W_r - \Delta W_r,\ \forall r \in \{0,1,\cdots,R\} \tag{4.2-15}$$

From physical constraints we have

$$W^{\min} \le W_r \le W^{\max},\ \forall r \in \{0,1,\cdots,R\} \tag{4.2-16}$$

It is possible not to impose physical constraints on the amount of release, because they always apply due to technological constraints

$$\phi(W_0^r) + \Delta W_r \ge W^{req} \tag{4.2-17}$$

where W^{req} is the requirement dictated by sanitary standards, navigation conditions, etc. Now we can formulate the criterion of managing the basin and the LSR

$$L = \min_{\Delta W_r}[\alpha_1 \sum_{r\in\{R\}} f_1(D^r) + \alpha_2 \sum_{r\in\{R\}} f_2(W^M - W_r)] \qquad (4.2\text{-}18)$$

where α_1, α_2 are Paretto coefficients ($\alpha_1 + \alpha_2 = 1$), $f_1(D)$ is the function of damage in the basin from water shortage, $f_2(W^M - W_r)$ is the function of damage in the basin from undersupplied electric power.

From (18) we see that the strategy of managing the basin and LSR should have a two-component structure, i.e.,

$$\Delta W_r = Y(D_r, DW_r), \text{ where } DW_r = W^M - W_r \qquad (4.2\text{-}19)$$

Physically $\partial f_1/\partial D^r > 0$, $\partial f_4/\partial DW^r > 0$, therefore for any structure selected to seek an optimal strategy to manage the basin and LSR the following conditions should hold

$$\frac{\partial Y}{\partial D_r} \geq 0; \frac{\partial Y}{\partial DW_r} \leq 0,\ \forall r \in \{0,1,\cdots R\} \qquad (4.2\text{-}20)$$

In principle, we can invent an infinite set of structures $Y(D^r,DW^r)$ that satisfy the conditions of (20) (You have to select them precisely for each basin) and supply min L. Consider the simplest structure. Let

$$Y(D^r, DW^r) = \lambda_1 DW^r - \lambda_2 DW^r;\ \lambda_1, \lambda_2 \geq 0 \qquad (4.2\text{-}21)$$

We need to define λ_1 and λ_2 such that

$$L \to \min_{\lambda_1,\lambda_2} L$$

and the system's trajectory is described by expressions (11) – (14). Were flow values (W_0^r, $r = 1,2,\ldots,R$) determinate, then the problem of finding λ_1 and λ_2 would have a unique solution. However, taking into account the random nature of W_0^r, we actually face the problem of finding the values λ_1 and λ_2 that would be applicable for the entire set of samples W_0^r. Consider the algorithm of obtaining these values in detail. Suppose we have a set of sequences $\{W_0^r\}^s$, where s is the realization number, $s=1,2,\ldots,S$, S is the total number of flow sequences realizations. Now we can consider a specific realization of a flow sequence as a random vector w^s, ($w^s=\{W_0^1, W_0^2,\ldots, W_0^R\}$) and parameters of the structure of a management strategy as a vector $\boldsymbol{\lambda}$, ($\boldsymbol{\lambda}=\{\lambda_1, \lambda_2\}$). We can write the objective function of management strategy as follows

$$L^{\min} = \min_{\lambda} L(w^s, \lambda)\Big|_{w^s} \qquad (4.2\text{-}22)$$

In accordance with the realization of the flow sequence w^s**,** there will be λ^s with which the equation (22) reaches its minimum. Denote this minimum by $L^{s,min}$. The set $L^{s,min}$**,** and λ^s, $s \in \{0,1,2,\ldots,S\}$ form two sets, which we can also consider as random. Define averages of these values in the set $\{S\}$ by $M[\lambda^s]$ and $M[L^{s,min}]$. After that, calculate L_s as

$$L_s = L(w^s, M[\lambda_s]),\ \forall s \in \{0,1,\cdots S\} \qquad (4.2\text{-}23)$$

Physically $L > 0$, hence the following inequality should apply

$$M[L_s] \geq M[L^{s,\min}] \qquad (4.2\text{-}24)$$

Now we can introduce a measure that characterizes the quality of the selected structure of management strategy

$$\delta_Y = \frac{M[L_s] - M[L^{s,\min}]}{M[L_s]} \qquad (4.2\text{-}25)$$

The better the management strategy structure we select, the less δ_Y will be (for an ideal management strategy $\delta_Y = 0$). For actual water management complexes, this management strategy is greatly simplified, because it lacks even environmental requirements. However, under any complications of structures and criteria, the stated principles of seeking a management strategy and the formulated constraints on the solution space will hold.

4.2.4. Problems of Multi-year Regulation in the Syrdarya Basin

The major LSR of the Syrdarya River were designed using multi-year average and annual average flow characteristics. The design was based on water use in the long term and supposed a single economic area for the entire river basin. The formation of four sovereign countries with independent economic criteria in the Syrdarya basin fundamentally changed the point of view on methods of regulating river flow by LSR. Indeed, let ΔW be the additional guaranteed water diversion obtained from operating long-term storage reservoirs, because LSR do not increase the total river flow, but only reallocate it in time.

With the same degree of reliability, we can state that lower river reaches will be undersupplied by the amount $\Delta W + \delta W$, where δW are inevitable losses occurring as a result of regulation (evaporation, filtration, escapages). Considering water rights of each country defined by interstate agreements, LSR face with quite a different task, namely to provide proportional (according to water availability of a year) flow allocation between countries of the river basin. Changed requirements of the functioning of LSRs created several additional problems in operation. These problems result from both technical (the complex of hydroengineering facilities located downstream from the LSRs has limited carrying capacity in winter) and economic difficulties. The latter ensues from the fact that farming areas needing guaranteed water supply and the LSR implementing this guarantee generally belong to different countries. For instance, the major long-term flow regulator in the Syrdarya basin is Toktogul reservoir in the Kyrgyz Republic. However, farming areas needing guaranteed water supply are in the Republic of Kazakhstan and the Republic of Uzbekistan. Consequently, the Republic (in this case Kyrgyzstan) that implements long-term flow regulation has a right to require compensation for costs from the Republics that use the results of its regulation activity.

At the same time, the energy biased operation of Toktogul reservoir increased operating costs. In addition, what is most important, it resulted in loss of water resources in low water years (discharges to Arnasai Depression) in Uzbekistan and Kazakhstan, because of higher water release in winter. Such uncoordinated activities of different water users result first from the lack of justified criteria to carry out economic appraisal of consequences of some or other water regulation policy. Now Central Asian countries widely practice mutual off-sets on water resources based on an energy equivalent (the cost of additional release is either the cost of undersupplied electric power if water was discharged through hydroelectric power stations or on the difference between summer and winter costs of electric power, if release was in summer). However, this practice often proves unworkable, because in most cases it is not clear what part of the release is supplied due to multi-year regulation and therefore should be paid and what part is a natural component of river flow.

It may not be justified to extend the equivalent of undersupplied electric power to the total amount of water resources flowing through the hydroelectric power stations. The reason is that in this case most agricultural production located in the command area of LSR will be either unprofitable, if we deduct compensatory difference from profits of economic entities, or unsupplied with water, if we run the multi-year storage reservoir solely under the energy mode. Thus, the economic interrelations being established by Central Asian countries have shifted the emphasis in functioning of LSRs from maximum available water diversion from the river basin to uniform (in terms of availability) water allocation between countries – water users and water consumers. In addition, the role of LSR as energy entities with stable economic income grew substantially, and consequently their (LSR) impact on seasonal reallocation of river flow increased.