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THE STOCHASTIC ASPECTS OF LONG-TERM WATER RESOURCES PLANNING AS APPLIED TO THE INTEGRATED REGIONAL DEVELOPMENT PROBLEM

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May 1979
CP-79-4

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PREFACE

Water resources systems have been an important part of resources and environment related research at IIASA since its inception. As demands for water increase relative to supply, the intensity and efficiency of water resources management must be developed further. This in turn requires an increase in the degree of detail and sophistication of the analysis, including economic, social and environmental evaluation of water resources development alternatives aided by application of mathematical modeling techniques, to generate inputs for planning, design, and operational decisions.

During the year of 1978 it was decided that parallel to the continuation of demand studies, an attempt would be made to integrate the results of our studies on water demands with water supply considerations. This new task was named "Regional Water Management" (Task 1, Resources and Environment Area). It is concerned with the application of systems analysis techniques for planning and operational management of integrated regional water resources systems.

This paper by Dr. S. Velikanov from the Institute of Water Problems of the USSR Academy of Sciences was drafted during his short visit to IIASA in early 1978. It reviews some of the approaches developed in the USSR concerning estimation of reliability of water supply and water demands and the use of these reliability estimates in the water resources planning process.

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Water resources occupy a prominent place on the list of natural resources determining the possibilities of economic growth. Rapid advances in industry and agriculture and improvement of man's living conditions result in an unprecedented increase in water demands and diverse uses of natural water resources. Water supply for developing communities has become one of the most important problems of today, and this problem may be solved only by the establishment of major water resources.

A water resource system is understood to be a hydraulically related totality of water sources and facilities for water transfer and supply to water users, as well as measures making possible the use of water resources in their natural state. Streamflow is and will be the main water source on the earth now and in the foreseeable future. Therefore, when speaking about water resources systems we mean, above all, systems based on river systems and large lakes.

Water resources systems, like electric power, transport and other technological systems created by man, have become important components of regional and national development in today's world. Water resources systems, however, differ greatly from the majority of other technological systems, particularly in the character and the use of the resources -- water.

Unlike other natural resources on the earth, water resources have been discovered almost to their full extent. The task of the researchers now is not to discover new supplies, but to use rationally the water resources provided by nature. In this connection, recognizing the streamflow fluctuation patterns is one of the principal requirements of the systems approach to the analysis of water resources. These fluctuations are governed by some probabilistic laws. Streamflow prediction for long periods, for the time spans of regional development planning, may be only on the probabilistic basis. It is natural that our knowledge of the streamflow fluctuation patterns will improve, but at best the transition from unconditional to conditional probability distribution curves, where other geophysical processes may be a predictor, is possible. Unfortunately, the fluctuation patterns of other geophysical processes, within the time horizons of development planning, also have a probabilistic character. The above observations indicate that the probabilistic nature of the fluctuations of water resources is one of the important characteristics which cannot be disregarded in the planning process for water resources development and water supply in particular.

Another, no less important feature of water resource systems is the character of water resources use. The majority of water users (with the exception of irrigation, which basically differs from other water users) consume irretrievably only a small fraction of water withdrawn from a source and then return most of the water withdrawn back to the source. For example, thermal electric power plants -- one of the most water intensive branches of all national economies, requiring a large amount of water per unit of output -- consume irretrievably no more than 9-10 km^3 of water per year in the world, and the world's oil producing industry is now consuming irretrievably about 5 km^3 of water per year [Velikanov, 1977]. On the other hand, the U.S. thermal and nuclear electric power plants alone withdraw annually about 300 km^3 of water [Davis and Wood, 1974]. A similar situation exists in other branches of industry and municipal economy. Thus, repeated use of water and interrelation of individual water users in a system, both in terms of water withdrawal from a source and in terms of water quality variations resulting from water use in production processes, are factors to be considered in water resources development planning.

Particular attention should be paid to the main water user, agriculture, which consumes irretrievably the largest amount of water and seriously affects the quality of water as a result of irrigation run-off and washing off fertilizers, pesticides and insecticides from the fields. This impact of agriculture on water quality is difficult to control and is currently receiving much attention.

In the author's opinion, the problem of water demands for irrigation is not being solved correctly. The majority of researchers estimating irrigation water demands proceed from present agroclimatic and water management conditions. Practically, the problem amounts to the selection of agricultural production parameters under deterministic conditions. The stochastic variability of agroclimatic and water management conditions is at best replaced by consideration of a number of different cases estimated according to probability weights (mathematical expectation). The problem, however, consists not only of selecting an optimal structure of agricultural production in the field, farm, district, or region with a preset water availability, but also of giving rules for management of agricultural production with stochastic prediction of both agroclimatic and water management conditions. As shown by G.V. Voropaev in 1973, this problem, like the problem of the operational management of water resources systems discussed below, is classified as a stochastic problem of management. Unfortunately, experts in the fields of optimization of water resources systems and water demand seem to be unfamiliar with this study, which clearly shows that to estimate properly the regime of water use in irrigation, it is necessary to: (1) evaluate beforehand, in probabilistic terms, the possible conditions of system operation under conditions of both excessive and deficient water availability; (2) work out rules for system development, taking into account the conditions of water availability specific for a given country; and (3) make a real estimation of the efficiency of the selected water use parameters. Other sources show that similar methods for estimating water demands in irrigation are being used in developing the Texas Water Plan in the USA. It would be desirable to discuss both of these approaches together.

Streamflow fluctuations and lack of agreement between the capacity of a source and water demands of different water users also call for a special approach to planning water resources systems. Even recently, in the case of a single-purpose use of streamflow, the possibility of obtaining the required amount of water was rigidly related to the fluctuations in the yield of a water source. The stochastic character of these fluctuations was taken into account by analysis of natural streamflow data recorded in the past. The concept of the firm yield of a source was also introduced at that time, thus determining the lowest water conditions in a river. As water demands increased, the firm yield of a source had to be increased by construction of storage reservoirs and runoff regulation. However, increasing storage capacity proved to be economically inefficient in the case of reservoirs providing regular water supply to water users. In this case, the usable storage of reservoirs would be seldom utilized, since a number of water users might give up the high reliability of obtaining the required amount of water at the expense of increasing their water demands. Thus the problem of probabilistic estimation of reservoir capacities emerged as the first problem in planning water resources systems.

The solution of this problem must take into account three interrelated important parameters of a water resources system: usable storage of a reservoir; its yield (water supplied to water users); and the reliability of water supply. In the Soviet Union, this problem is called run-off regulation, and it was studied extensively by the scientific school guided by S.N. Kritskii and M.F. Menkel [Kritskii and Menkel, 1952; Korenistov et al, 1972]. The proportions between reservoir storage, yield and supply reliability are the basis for planning water resources systems. The economic measure of water demands may be a water demand function, as shown by work done in a number of countries and at IIASA. The economic estimation of reservoir construction presents no special problems, though it is appreciably complicated by the need for consideration of their environmental impacts

The problem of the substantiation of the reliability of water supply to water users is most complicated both as to methodology and practice. One of the possible solutions to this problem has been suggested by the author of this paper [Velikanov, 1973; Velikanov and Korobova, 1976]. The principles of this method are presented below. The concept of estimated probability characterizing the probability of regular water supply to various water users is being used widely in planning water resource systems in the Soviet Union [Kritskii and Menkel, 1952; Velikanov, 1977]. The reliability index was first used in planning the development and management of water resources systems many years ago, and it now forms the basis of all water management projects. However, as shown in recent studies, this index is insufficient under complex water resources use conditions [Korenistov et al, 1972], and this complicates considerably the problem of planning water resources systems.

As noted above, both streamflow and water demands in irrigation are of a probabilistic character. Therefore, along with estimations of reservoir needs using a series of historical or simulated hydrologic sequences, one must consider the problem of developing rules for management of water resources systems, taking into consideration the real possibilities of predicting inflow and climatic conditions. At this point, we do not know of practically applied analytical methods for solving the problem of developing operational rules for management of multiple-purpose water resource systems. The methods currently in use are based on simulation experiments, which are quite promising as a result of the application of computer techniques. In the development of the Texas Water Plan, the problem of the management of a cascade of reservoirs was solved by simulating the operation of a system under different water availability conditions with simultaneous minimization of expenses and penalties emerging in case of water shortages [Economic Opimization, 1974]. Unfortunately, the available materials do not give a clear idea of the technique of these operations or of the functions describing economic losses due to periodical water shortages. The character of these functions seems to govern largely the mathematical model of management. The USSR and Texas Water Development Board researchers seem to have fairly close opinions concerning this problem.

Some features which should be considered in water resources planning as applied to the regional development problem have been discussed briefly above. It is clear, moreover, that a water resource system should be considered as a whole. It is impossible, for example, to separate determining the parameters of water users from determining the water supply reliability. Let us consider the problem of reliability in relation to planning water resources systems.

As stated above, for each water course there exists a definite dependence between the firm supply and its reliability; the larger the firm supply the smaller its reliability. The reliability can be increased by regulating the flow with storage reservoirs. But flow control by reservoirs changes only the proportion between the guaranteed amount of water supplied to users and the reliability of water supply. For this reason, the problem of selecting an appropriate level of water supply does not disappear with the determination of the water user's parameters.

The problem of water supply reliability is a problem of selecting optimum parameters of a water resource system. If costs are taken as a criterion of optimality, the problem can be reduced to maximization of the difference between economic benefits (expense reductions) due to the increase in the productive capacity of water-using activities and the sum of costs of increasing the reliability of water supply and damages inflicted on the water-using activities, when the required supply cannot be ensured due to the water deficiency.

$$E(X) - [C(V) + Y(X,V)] \longrightarrow \max \qquad (1)$$

Where

$E(X)$ = expense reductions by increasing water use up to a value X,

$C(V)$ = costs of construction of storage reservoirs with the capacity V,

$Y(X,V)$ = damages due to water shortage with estimated water demand of X and storage capacity of V.

Despite the fact that this problem seems to be a very simple one, its solution presents numerous difficulties. These difficulties are basically caused by the necessity of estimation of economic effects due to disruptions in normal water supply (damages). This problem is solved in different ways in different countries.

As stated above, in the Soviet Union a reliability index is applied to solve this problem. This index provides a probabilistic standard for uninterrupted water supply and is established, as a rule, on the basis of water management experience. The estimated reliability, as a standard or criterion for interrupted (regular) water supply, is defined separately for various branches of the national economy and takes into account the reaction of water users to disruptions in normal water supply.

The estimated reliability indices used in the USSR may be applied to the three broad categories of water users [Kritskii and Menker. 1968].

1. Users requiring practically uninterrupted water supply: their demands are estimated on the basis of a 95-99 percent reliability (e.g. 95% reliability means that during a period of 100 years deficits are allowed to occur in 5 years).
2. Users that can afford more or less frequent deviations from the normal water supply regime; a 85-90 percent reliability; and
3. Users that demand large amounts of water per unit production, that have reserves and tend to use most completely the excess of streamflow; a 75-80 percent reliability.

The first category includes municipal water supply, industry and large hydropower plants with long-term streamflow regulation playing an important role in the energy production system. The second category comprises river transport and small hydropower plants. The third category includes agriculture and fisheries.

The estimated reliability of water supply is the most simple and convenient index and is employed to determine the parameters of water resource systems.

However, this index does not take into account the water supply regime and therefore, the working regime of reservoirs during the water deficit years. For this reason another index -- allowable depth of reduced water supply in the deficit years -- has been introduced into water management practices. For example, the estimated reliability of water supply for many irrigation systems in the USSR amounts to 90% and in 10 deficit years water supplies cannot be curtailed by more than 20% of the normally required supplies.

The experiences of the operation of large water resources systems has shown that the above indices of reliability do not fully take into account the ecological requirements involved in the use of natural resources.

The possibility of initiation of irreversible processes in ecosystems is not only related to the number of years and the depth of water supply interruption, but also depends to a large extent upon the duration of such phenomena. It was necessary, therefore, to introduce an additional index of reliability that characterizes the permissible duration of low-water year sequences. At present, this relationship index of water resources systems is not widely used, but the future of these systems looked upon as an element of the environment will be determined by this index to a large extent.

As mentioned above, until recently the problem of estimated reliability was considered, as a rule, separately for each particular branch of national economy. But the present state and future development of water management leads one to examine this approach.

An analysis of water resources systems as a combination of water sources and water users reveals some peculiarities of such systems. First, a direct relationship is no longer present between water demands of individual users and anticipated shortage of water because the latter is determined not by the streamflow variability alone, but also by the standing procedure of water resources distribution among water users. In addition, with system components scattered all over the river basin and the high differentiation of water use patterns (consumptive or non-consumptive withdrawals, use of the river's natural flow, etc.), the relationship between aggregate water demands and water shortages, with a definite storage capacity of reservoirs, proves to be uncertain. The reliability of meeting the demands of individual water users turns out to be the function not only of the run-off regulation, but also of some other factors, which cannot be taken into account by establishing estimated reliabilities separately for individual branches of economy.

In this regard, the problem of estimation of water supply reliability has been posed in the case of complex water resource systems as a problem of mathematical programming. The solution of this problem is based on the following:

(1) An increase in productive parameters and the output of each water user (component of a water resource system) is economically justified up to certain limits set up by comparative analysis of the alternative ways for obtaining a similar type of product;

(2) Under conditions described in (1), an increase in the production effectiveness of particular water users is related to an increase in the amount of water used;

(3) Under varying streamflow conditions, an increase in the required amount of water resources results in an increase of the probability of interruptions in water supply and an increase in their duration. This calls for careful economic analysis of such problems.

Thus, the problem of optimization of parameters of water resources systems can be reduced to a comparison of: (1) reduced expenses occurring as a result of the increase in parameters and effectiveness of water users compared against the alternative ways of obtaining a similar increase in benefit, and (2) the damages due to the periodical shortages of water supply [Korenistov et al, 1972].

For a multicomponent water resources system and for a fixed reservoir storage capacity, an expression can be written as:

$$\sum_{j=1}^{m} [E_j(X_j) - Y_j(X_j)] \longrightarrow \max \qquad (2)$$

Such a statement of the problem leads to economic estimation of basic parameters and the productive capacity of individual water users which constitute components of a water resource system. In this case, the estimated reliability indices lose the significance of a standard and serve only as characteristics of reliability of water supply to individual water users.

The problem of selecting parameters and determining the reliability of continuous water supply to the water users can be reduced to a problem of stochastic non-linear programming, precisely, to minimization of a certain function of expected expenses:

$$F(x_1,x_2,\ldots,x_m) = \sum_{j=1}^{m}\{C_j(X_j) + C_j^{alt}(G_j-X_j) + M[\min\sum_{j=1}^{m} Y_j(D_j)/X_j]\} \qquad (3)$$

where,

X_j = estimated water demand which determines parameters and efficiency of the j-th water user ($X_j \leq G_j$);

$C_j(X_j)$ = estimated expenses for realization and functioning of the j-th water user;

$C_j^{alt}(G_j - X_j)$ = estimated expenses for an alternative to achieve the required production effectiveness;

$M[\min\sum_{j=1}^{m} Y_j(D_j)/X_j]$ = expected value of the total losses due to the shortage of water supply, minimized over all water users located in a given water resources system;

m = number of water users;

This problem may be solved in two stages [Velikanov, 1973]; for every fixed value of a vector of optimized parameters $X = (X_1, X_2 \ldots X_m)$ an optimization problem of water resources allocation is solved.

The problem of water resources allocation in a complex water resources system with fixed parameters of water users has been solved using dynamic programming, as reported at the Second World Congress on Water Resources by Velikanov and Korobova (1978). The use of statistical methods for the solution of this problem had been considered earlier [Velikanov and Poizner, 1976].

The mathematical and computational aspects of the problem of water supply reliability in a water resources system have been discussed above, but the problem is not yet solved. The possibility of obtaining initial information to solve the optimization problem is of no less importance. First, it relates to the estimation of interruptions due to water supply shortages, the so-called damages. It should be admitted that the methods for estimating damages due to water supply shortages have not been developed fully, and their qualitative estimation is difficult. Under these circumstances, one has to resort to the introduction of a standard damages values [Kritskii and Menkel, 1968; Velikanov, 1973] which allows for a more precise solution of many water management problems.

Such an approach differs radically from the commonly used reliability standards for continuous water supply. The standard value of losses is controlled only by economic characteristics of a given water user and by the user's reaction to the shortage in water supply, and can be determined without regard for the other water users which constitute components of a water resources system. On the other hand, it is not possible to fix the reliability of continuous water supply without taking into account the interaction of individual components of a water resource system, as shown by experiments conducted by the author using a simplified optimization model of a water resources system.

The optimization model can also be employed in analysis of the reaction of a water resources system to the variation in damage indices. Standard values of damages can be assigned within a wide range and can take into account the non-economic significance of continuous water supply to a certain user and requirements of the ecosystems. The economic and water management estimates, obtained as a result of optimization, can serve as the basis for decision-making.

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