term operation of a single multipurpose reservoir." *Water Resour. Res.*, 25(1), 1–8.
Wanka, K., and Königer, W. (1984). "Unsteady flow simulation in complex drainage systems by HVM-hydrograph volume method." *Proc. 1st Int. Conf. on Channels and Channel Control Structures*, Southampton, England, 5.17–5.31.
Wasimi, S. A., and Kitanidis, P. T. (1983). "Real-time forecasting and daily operation of a multireservoir system during floods by linear quadratic gaussian control." *Water Resour. Res.*, 19(6), 1511–1522.
Winn, C. B., and Moore, J. B. (1973). "The application of optimal linear regulator theory to a problem in water pollution." *IEEE Trans. on Systems, Man, and Cybernetics*, SMC-3(5), 450–455.

Appendix IV. Notation

The following symbols are used in this paper:

$\mathbf{A}$ = system state matrix;
$\mathbf{B}$ = input matrix;
$\mathbf{C}$ = output matrix;
$\mathbf{d}$ = disturbance vector (external inflows);
$\mathbf{d}^N$ = vector of nominal inflows;
J = cost criterion;
K = time step index at end of control horizon;
k = time-step index;
$\mathbf{L}$ = feedback gain matrix;
$\mathbf{P}$ = solution matrix of matrix-Riccati-difference equation;
$\mathbf{Q}$ = weighting matrix for deviations from nominal state;
$q_{in,i}$ = inflow of reservoir i;
$q_{in,i}^N$ = nominal inflow of reservoir i;
$q_{out,i}$ = outflow of reservoir i;
$q_{out,i}^N$ = nominal outflow of reservoir i;
$q_{out,i}^{max}$ = maximum outflow capacity of reservoir i;
$q_{over,i}$ = overflow of reservoir i;
q_{plant} = inflow to treatment plant;
q_{plant}^N = nominal inflow to treatment plant;
q_{plant}^{max} = maximum admissible treatment plant inflow;
$\mathbf{R}$ = weighting matrix for control reactions;
r_i = diagonal element of weighting matrix $\mathbf{R}$;
T = sample time interval of control;
$\mathbf{u}$ = vector of control inputs;
$\mathbf{u}^N$ = vector of nominal control inputs;
V_i = storage of reservoir i;
V_i^N = nominal storage of reservoir i;
V_i^{max} = maximum storage of reservoir i;
V_T = total storage of all reservoirs;
$\mathbf{V}$ = vector of storage;
$\mathbf{x}$ = state variable vector;
$\mathbf{x}^N$ = nominal state variable vector;
α_i = weighting factor for the reservoir i; and
λ = Lagrange multiplier.

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Planning and Management of Water-Resource Systems in Developing Countries

Document

By M. Miloradov[1]

Abstract: The multipurpose use of water in all types of human activities and the intensive development and urbanization of settlements have resulted in a considerable increase in water demand and water pollution. This is why it is necessary to build complex, spatially scattered, multipurpose water-resources systems. The multiple objectives and limitations encountered in the planning and management of such systems result in the multidimensional mathematical formulation of the problem and in the application of complex models that need to be simplified. Their simplification often makes the obtained results and the influence of different criteria and limitations on the choice of a final solution somewhat unclear. To eliminate these weak points in the planning of complex water-resources systems, a multiphase optimization procedure is developed, leading to the development of complex, multipurpose water-resources systems.

Introduction

Developing countries are often in a very specific situation when it comes to planning and developing water resources. The intense development of the economy and the rapid urbanization of settlements generally result in an increased water demand and more pollution of the available water resources. Furthermore, because of the more intense development that takes place in the river valleys, there is also a greater need to provide appropriate protection against the possible adverse impact of water. This means that as far as water-resources development is concerned, developing countries need to move very quickly from the so-called natural state of a river basin to the developed stage.

Because of the low level of development in the natural state, the water demand can be met by simply using the local natural water resources so that no major works need to be done to regulate the flow regime. The water quality is good, and the amount of wastewater is small and does not exceed the natural self-purification capacity of the ambient waters.

However, in the developed stage, the water demand exceeds the natural capacity of the existing resources. It is therefore necessary to build river engineering structures to collect and transfer water from where it is available to consumers and major wastewater treatment plants. It is also necessary to ensure flood control because of the many valuable structures built in the river valleys.

In situations like this, planners face many very complex problems. This is why it is essential to consider multiple objectives and implement the analyses, bearing in mind the spatial and temporal characteristics of water-resources systems and their dynamic nature.

In the planning phase, when doing the analysis and synthesis of such systems as well as when mathematically formulating the problem, planners

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are faced with multidimensional problems that require the use of complex models. These models usually need to be simplified for planners to be able to deal with the problems efficiently; this in turn makes the obtained results somewhat uncertain. Furthermore, it does not provide a clear picture of how the adopted modeling criteria and model limitations affect the solution, nor does it provide information on how big a risk is taken if the wrong choice is made in the planning phase.

The analyses and investigations in the planning stage of the project should provide decision makers with reliable information on the possible consequences of the implementation of a suggested water-resources development project. Based on this information the decision makers need to reach a decision with the minimum of risk.

This paper describes some of the Yugoslav experience in planning the development of water-resources systems.

General Approach to Planning and Management of Water-Resources Systems

The multipurpose use of water for all types of human activities as well as the need both to provide protection against the adverse impact of water and to protect water as an environment inhabited by different life forms clearly show that the planning, management, and use of water resources are closely related to the planning and development of the entire economy and society in the broadest sense.

The development of plans for the management and use of water resources must be regarded as an interactive process (Fig. 1) that begins with the development of a national plan of physical and economic development on one hand and the development of water-resources master plans (regional or watershed related) that support such development on the other hand (Haimes 1977).

When developing a plan, it is most important to determine the most rational solution that will allow the available water resource to be transformed into a required resource, bearing in mind quantity and quality. It is clear that the existing problems and the goals that need to be achieved are being considered (Loucks et al. 1981; Major and Zenton 1979).

In this phase of planning it is best to use the so-called systems approach (Biswas 1976; Hall and Dracup 1970; Loucks et al. 1981). The water-resources plan should determine the most rational solution [from the point of view of the economy, society and environmental protection (Miloradov and Oprivic 1982; *Guidelines* 1985; *Management* 1985; Opricovic 1986] that would make it possible to transform the available water resource defined by vectors $\mathbf{Q}_R$ (available quantity), $\mathbf{K}_R$ (available quality), and $\mathbf{L}_R$ (location) into demand vectors ($\mathbf{Q}_p$, $\mathbf{K}_p$, $\mathbf{L}_p$):

$$\mathbf{Q}_R, \mathbf{K}_R, \mathbf{L}_R \rightarrow \mathbf{Q}_P, \mathbf{K}_P, \mathbf{L}_P \quad \ldots\ldots\ldots\ldots (1)$$

When doing this transformation, it is essential to bear in mind the existing need to ensure water protection and provide protection against the possible adverse impact of water. It is just as important to take into consideration all the physical plans and the social development of an area. Fig. 2 is a schematic presentation of the described transformation (Miloradov and Simonovic 1985; Miloradov et al. 1986).

The systems approach to the problem involves: (1) The definition of objectives; (2) the compilation of data and analysis of the problem; (3) the

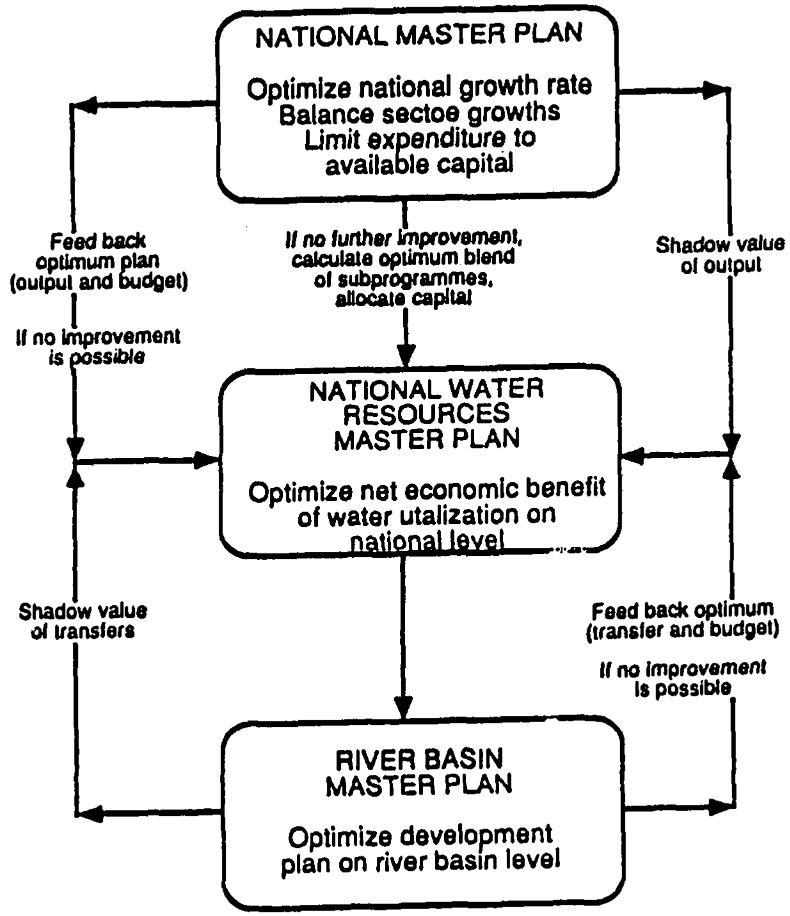

FIG. 1. Flow Diagram of Three-Level Interactive Planning System (after Haimes 1977)

analysis of available water resources; (4) the analysis of water demand and of the need for water protection; (5) the development and definition of alternative solutions; (6) the generation of alternative solutions; and (7) the choice of the optimal solution.

The flow diagram given in Fig. 3 is an outline of the plan applied for the optimal development and use of water in a river basin or at a national level. The two sets of activities might appear to be independent, but they cannot be developed separately without one influencing the other, and they are elements of a unique process.

Since it is well known how the different activities presented in the plan should be performed, there is no need for this to be discussed further in this paper. The most important part of the work consists of selecting the right methods and evaluating the optimal solution.

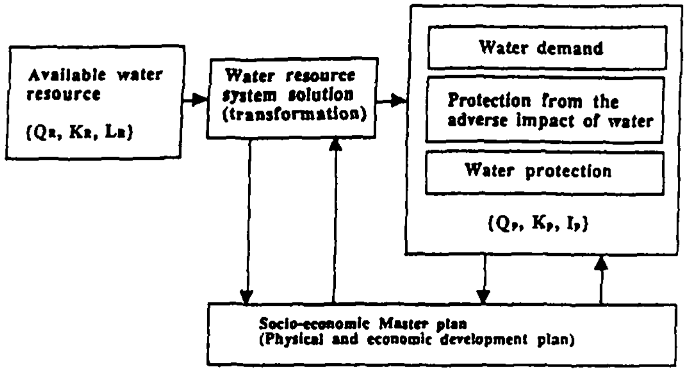

FIG. 2. Objective of Water-Resources Master Plant

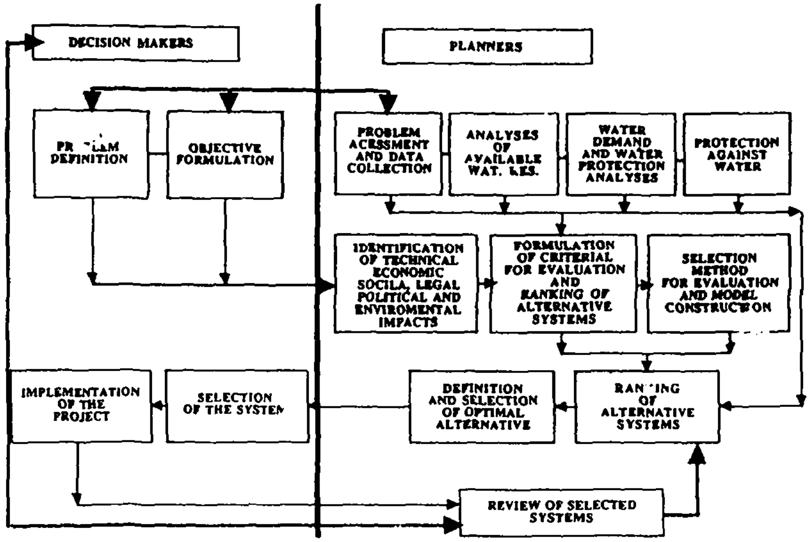

FIG. 3. Outline of Planning and Decision-Making Process [after Miloradov and Simonovic (1985) and Miloradov et al. (1986)]

Definition of Objectives and Criteria for Evaluation of Optimal Solutions

The general approach clearly shows that decision makers need to define the objectives they wish to achieve through the implementation of water-resources systems. However, this is very difficult to do in actual practice because of the many people involved in the decision-making process and the multipurpose use of water-resources systems. The interests of different parties are not always the same but they do need to be considered and fulfilled.

With this in mind, planners need to analyze the entire structure of the objectives of a water-resources system at several levels, with clearly defined

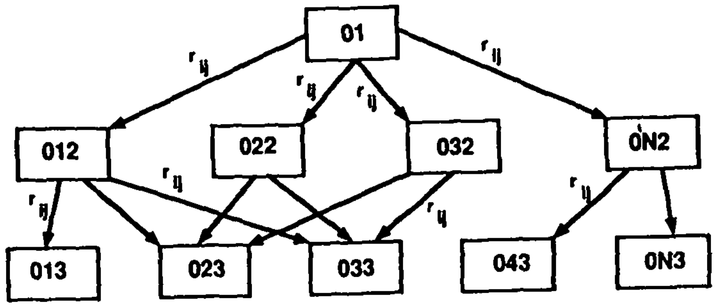

FIG. 4. Possible Structure of Objective (i = Objective Number, j = Objective Rank)

connections, bearing in mind how they are ranked. In doing so, the highest-ranked objective can be divided into several lower ones (Fig. 4).

In the given structure the objectives may be connected by means of the "and" logic, which implies that all the lower-ranking objectives must be realized, or by the "or" logic, which implies that by means of optimization, it would be possible to realize one or another objective or a group of objectives.

The criteria functions used for defining the realization of certain objectives can be expressed:

1. Using quantitative parameters (such as quantity of supplied water, quality of supplied water, hydropower production, average flow, and area protected against flooding).
2. Through the operational reliability of the system (required operational reliability of the system, flood frequency, and probability of low water levels).
3. With economic parameters (benefit-cost ratio, B/C; net profit $B - C$; and similar parameters).
4. By evaluating the intangible parameters important for the realization of the desired objectives (importance of a system for a specific region, suitability for incorporating into other solutions, determination of whether a system can be built in phases, the intangible effect on society and the environment, and similar parameters).

By defining the structure of the objectives and the criteria functions in this way, it is possible to point out the complexity of the problem and show how difficult it is to determine the best solutions when planning and managing a water-resources system. On the other hand, this clarifies which direction to take to achieve the desired solutions and analyze how certain criteria affect the choice of a recommended solution.

Determining Water Demand

Forecasting future needs directly depends on the planned process of urbanization and the economic development of the region for which the plans are being developed so that the physical, economic, and water-resources development plans are clearly interrelated.

The water demand must be determined separately for all the basic water consumers: (1) Settlements; (2) industry; (3) agriculture (irrigation and cattle rearing); (4) fishing; (5) power supply; and (6) other consumers.

In developing countries, there has been a rapid increase in the water demand of settlements. In conditions where there is no public water-supply system, the average water consumption per capita ranges between 5 and 50 l/capita/day. *In urban conditions* where the standard of living is higher and local industries are connected to the public water-supply system, water consumption rapidly increases to anywhere between 250 and 550 l/capita/day and even 600 l/capita/day (Falkenmark and Yu 1976).

Since the urbanization of settlements and the construction of a water-supply network result in a greater number of consumers connected to the network, there is an increase in consumption; and the water demand in such situations tends to increase very rapidly. The situation is similar with the increasing needs of industry, irrigation, fishing, and power production, and the increased water demand in these cases is even more closely related to the investment in the construction of new production capacities (*Management* 1985).

Since there is a rather fast increase in demand, it is very difficult to make any reliable forecasts. Therefore, instead of assuming only one solution, it is wise to evaluate a range of solutions within two boundary conditions while giving one most probable mean value, as shown in Fig. 5.

Definition of System Solution

The definition of alternative system solutions basically depends *on*: (1) The available quantity and quality of the water resources in a watershed; (2) the required quantity and quality of water resources with respect to time and space; (3) the need to ensure water protection and provide protection against the adverse impact of water; and (4) the topographic characteristics of an area, i.e., the possibility of regulating a water regime, enabling the use of the waters, and providing the required protection.

The characteristics of an available water resources depend on the hydrological analyses of the natural state of a watercourse and on the number of hydraulic structures built on it. The methods used for these analyses are well known. They basically consist of analyzing and processing the time series showing the water quantity and quality at characteristic profiles along a watercourse.

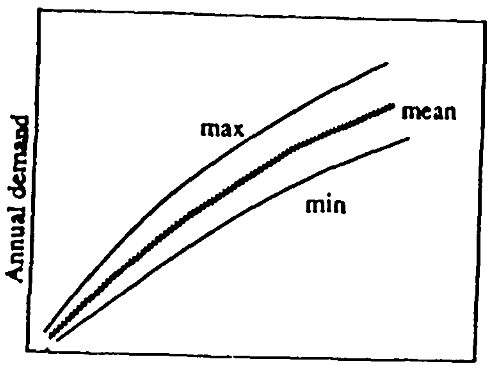

FIG. 5. Demand for Water as Function of Time

The basic procedures used to determine the quantity and quality of the water required by all consumers in a watershed have been described previously. However, it is also necessary to determine the need to provide water protection and ensure protection against the adverse impact of water.

To do this, it is absolutely essential to determine the amount of wastewaters and analyze their quality. It is also important to know how much wastewater and of what quality a watercourse can receive during a critical period.

Furthermore, a study must be done of the damage caused by floods in an endangered area and of the characteristics of floodwaters relevant for determining the required level of protection.

To solve these problems, it is necessary to develop complex models of physical processes, namely water flow in the natural channels. The problem of water-quality control also requires the modeling of biochemical processes in open flows and reservoirs.

The topographic features of an area are needed to provide all the technical solutions relevant to the construction of a dam and other related structures, to determine the cost of construction as a function of the height of a dam, and to rank the alternative solutions and select the most suitable one.

Once there are available data on the potential reservoirs and their storage capacities, it is possible to analyze the water supply and formulate the alternative solutions that would meet the water demands of different consumers while developing a system for the preparation and treatment of the water and its transport to the consumers.

It is also necessary to calculate how much the water treatment and transport to consumers costs, since this can have a significant bearing on which solution is best. The alternative solutions developed in this way are by no means final solutions, nor are they necessarily the optimal solutions. For the solutions to be developed, it was first necessary to do important hydrologic analyses and relevant computations to determine the characteristics of the available water resources; the existing and future water demands; and all the alternatives pertaining to the possible storage of water, the protection of water, and protection against the possible adverse impact of water (Miloradov and Tomanic 1985).

Methods and Procedures for Optimal Analysis of Water-Resources Solutions

General Systems Approach

Generally, it can be said that the problem of planning in water-resources development consists of determining system S, which transforms the water resource Q into the amount of water that needs to be supplied, $U(S{:}Q \rightarrow U)$. The measure of closeness to the water demand D is minimized, so that $\min\|D - U\|$.

If we look at things formally, the optimization procedure can be defined as OP: $M, G, J \rightarrow x^+$, where OP transforms the M, G, J trio into the optimal value of the decision within the decision-making area, M is a description of the system, G is the limitations, J is the optimization criterion, and x^+ is the optimal decision or solution.

When planning the development of a water-resources system, the following represent unknown variables: system parameters A(configuration) and variables determining the water demand and supply U, so that $x = (A, U)$.

The problem of optimization can now be written as $\max_{(A,U)} J(s, U, A)$, which usually develops into $\max_{(A)} [\max_{(U)} J(s, U, A)]$. This determines the optimal configuration of the system for the optimal distribution of water. The vector denoting state s in the system represents the volume of water in the reservoirs.

With complex water-resources systems, as mentioned earlier, it is essential to transform the available water resource at location $\mathbf{L}_R$ into the required resource at location $\mathbf{L}_P$. In this case the problem of distribution is defined as the transformation MP:

$$\mathbf{L}_R, \mathbf{Q}_R, \mathbf{K}_R \rightarrow \mathbf{L}_P, \mathbf{Q}_P, \mathbf{K}_P \quad \ldots\ldots (2)$$

Because the multipurpose use of water at times of intensive development (such as water supply to settlements, industry, agriculture, fisheries, power production, navigation, tourism, and sports) becomes everyday practice, and because water resources are not always located where they are most needed, it is clear that there must be several alternative solutions to be able to meet the existing water demand. However, because the water demand changes in time and water resources are a function of both time and space, it is quite clear that the solution is not unique and that it is difficult to find an optimum one. To simplify the problem, the complex system is usually broken down into simpler subsystems. This decomposition of the system can be done bearing in mind the purpose of water use, the available space, and the available time.

Complex water-resources systems can therefore be decomposed into a set of subsystems

$$S_i: Q_i q_i \rightarrow U_i u_i, \qquad i = 1, \ldots, n \quad \ldots\ldots (3)$$

where S_i = subsystems; Q_i = water resource of the ith subsystem; U_i = water supplied to the ith subsystem; q_i = water resource transferred to the ith subsystem; and u_i = water transferred from the ith subsystem.

The value of U_i is determined by means of local allocation; u_i and q_i, $i = 1, \ldots, n$, are determined through the aggregation of the system. The aggregation is the outer loop of the optimization algorithm and the subsystem optimization is the inner loop.

Variables q_i and u_i, $i = 1, \ldots, n$, represent the links between the subsystems. They can be determined by using the search method. The optimization of a subsystem consisting of multipurpose reservoirs can be done by means of dynamic programming. However, we often deal with very complex multipurpose systems that consist of several reservoirs and several alternative solutions that lead to the development of complex models. This is especially true when dealing with a system that has more than two or three reservoirs and when several combinations are possible.

The so-called multiphase optimization procedure has been developed and implemented for the optimal planning of complex water-resources systems.

Basic Phases in Multiphase Optimization Procedure

The multiphase optimization procedure basically consists of four phases:

1. The first phase consists of determining the water-related possibilities of every reservoir or of a group of reservoirs using different values for the storage space. It also includes an analysis of how a reservoir can influence the reduction of extreme flows relevant to ensure flood protection. In this

phase reservoirs are viewed as multipurpose sources of water supply containing variable quantities of water supplied to various consumers.

2. In the second phase, alternative solutions are provided for a group of consumers at the subsystem level or at the level of subsystems with two or more reservoirs.

3. The third phase of this procedure is done by implementing the multicriteria optimization method. It is possible to rank the available alternative solutions and choose the most appropriate one.

4. The fourth phase of the procedure consists of developing the possible solutions that can be applied for several subsystems or for the entire watershed. This is done using the computations and analyses performed in the third phase. The possible alternative solutions are then evaluated again using the multicriteria optimization method, primarily taking into consideration the higher-ranking criteria. By analyzing the obtained results, it is possible to propose a complex water-resources solution for an entire watershed or even for a whole country.

Short Description of Computation Methods Used in Optimization Procedures

To determine the possibility of using a reservoir for different water-related purposes, it is necessary to determine the permissible release of water from a reservoir taking into consideration different storage-capacity values and the existing inflows. The deterministic model based on the balance equation (continuity) and the organized retrieval procedure are used for this purpose.

The discrete form of the balance equation for a reservoir is:

$$V_i = V_{i-1} + Q_i - U_i - g_i \quad \ldots\ldots (4)$$

where V_{i-1} and V_i = volume of water in a reservoir at the beginning and end of the ith time interval, respectively; Q_i = inflow during the ith time interval (one month); U_i = total release; and g_i = loss of water from the reservoir.

The constraints on the water stage are given by $W_{min} V_i W$ for all i, where W_{min} is dead storage, and W is storage capacity of the reservoir. If a reserved storage is needed, then

$$W = W_{max} - W_{res} \quad \ldots\ldots (5)$$

The capacity required for retaining the flood, W_{res}, is determined by analyzing the flood transformation.

Whether a specific reservoir can meet a certain water demand can be determined using the Umax algorithm (Miloradov and Opricovic 1981).

When a system consisting of two or more reservoirs is considered, on the main river and tributary as shown in Fig. 6, the alternative systems that could meet the required demand are (1) Reservoirs R_1 and R_2; and (2) R_1 and R_3, or $R_I + R_J$ (J = 2, 3; I = 1).

The available water resource $U_I(W_I) + U_J(W_J)$ consists of the release from both reservoirs. To be able to meet the required water demand D, the following condition must be met:

$$D = U_I + U_J \quad \ldots\ldots (6)$$

The entire procedure has been explained in more detail by Miloradov and Opricovic (1981).

The determination of the possible discharge from every reservoir and

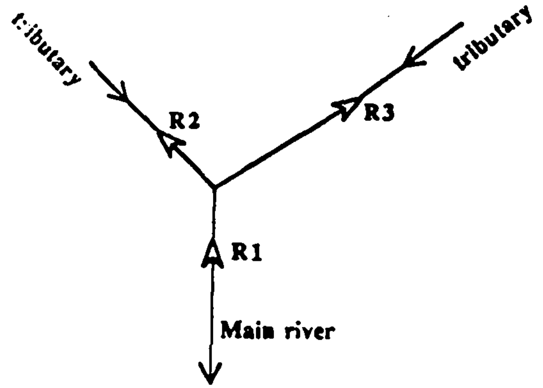

FIG. 6. Scheme of System

from the system of reservoirs using the developed procedures and the development of water resources subsystems represent the first and second phase of the multiphase optimization procedure.

In the third phase, to rank the alternative solutions taking into consideration multiple criteria, the compromise programming method is generally used (Opricovic 1986).

The ranking is performed by comparing the measure of closeness with the ideal alternative (Miloradov et al. 1990; Tomanic et al. 1988). One of the measures of closeness used is the L_p metric defined as follows:

$$L_p = \left\{\sum_{k=1}^{K} W_K \left[\frac{(f_{kn}^+ - f_{kn}^-)}{(f_k^+ - f_k^-)}\right]^p\right\}^{1/p}, \quad 1 \le p \le \infty \quad \text{(7)}$$

where $\Sigma_{k=1}^{K} W_k = 1$ = the weight of criteria ($W_k \ge 0$); f_{kn} = criteria functions, and f_{kn}^+ and f_{kn}^- = maximum and minimum values of f_{kn}. Parameter p plays the role of the balancing factor between the group utility and the maximum of the individual regret: As p increases, the group utility and the individual regret decreases. From the decision-making point of view, the compromise solution for $p = 1$ is based on the majority rule, while for $p = \infty$ it is based on the minimum-maximum strategy (Duckstein and Opricovic 1980; Goicoechea et al. 1982; Freimer and Yu 1976; Miloradov et al. 1990; Opricovic 1986; Opricovic and Djordjevic 1986).

In Yugoslavia, the iterative compromise programming procedure IKOR (Opricovic 1986; Opricovic and Djordjevic 1986) was developed, whereby the ranking is performed based on measure Q_j as given in the relation:

$$Q_j = V_1 \left(\frac{S_j - S^*}{S^- - S^*}\right) + V_2 \left(\frac{R_j - R^*}{R^- - R^*}\right) \quad \text{(8)}$$

where S_j = measure of the multicriteria ranking for $p = 1$; R_j = measure of the multicriteria ranking for $p = \infty$; $S^* = \min_{(j)} S_j$; $S^- = \max_{(j)} S_j$; $R^* = \min_{(j)} R_j$; and $R^- = \max_{(j)} R_j$.

In this case alternative Q_j (ordinal number j on the ranking list of alternatives) is better than alternative Q_k if

$$Q_j \le Q_k \quad \text{or} \quad q(a_j) \le q(a_k) \quad \text{(9)}$$

Position $q(a_j)$ on the ranking list depends on the values of f_{kn}, f_k^*, f_k^-, $k = 1, \ldots, n$. The values of f_k^* and f_k^- for several criteria are the values of the criteria functions for the best and worst alternatives, respectively. The influence of these alternatives on the position of the other alternatives can be avoided if the compromise ranking is done without them. The best alternative in the second iterative procedure will be ranked second on the ranking list. The iterative procedure is repeated until the entire set of alternatives has been considered.

The IKOR method makes it possible to determine the weight of the V_1 and $V_2 = (1 - V_1)$ decision-making strategies. If priority is given to satisfy most of the criteria without considering the fact that one criterion might not be satisfied at all, then $V_1 \ge V_2$ is chosen. However, if all criteria must be satisfied at least to a certain degree, a bigger value should then be determined for V_2. If $V_1 = 0.6$, the decision-making strategies are equal. In actual practice, the value of $V_1 = 0.3$ gives a sufficiently big advantage to the minimum-maximum strategy, which makes a compromise in the decision-making process possible.

Examples Showing Application of Procedure

The described procedure for the development of an optimal solution for complex water-resources systems was applied when developing several plans pertaining to the development of different basin areas in Yugoslavia. This paper is a brief review of the development of a complex water-resources solution for the Cesma river basin.

Cesma is a tributary of the Sava river and has a basin area of 2,530 km^2. The rivers begin at Kalnicko Gorje on the mountain slopes of Bilogora and at Moslovacko Gorje east of the city of Zagreb. The rivers have the greatest longitudinal slopes in the areas close to their source and then they very suddenly become watercourses flowing through the lowland valleys of the basin. The river basin resembles a fan, consisting mainly of hilly areas and lowlands. The biggest discharges are due to intensive rainfall. The average annual rainfall in the basin is about 900 mm.

The basic activities related to water-resources development in this area so far have consisted of building training structures on the Cesma and its tributaries as well as providing flood protection and constructing local water intake structures used for supplying water to fisheries and some bigger settlements.

When analyzing the development of water resources in this basin, the following problems were observed: (1) The water regime has not been regulated and there isn't a single bigger reservoir in the basin; (2) the water supply to the towns and industry is insufficient; (3) the agricultural areas are not irrigated at all; (4) the existing fisheries are supplied with insufficient quantities of water; (5) ground waters pose a threat to the low-lying areas that are also threatened by floods from surface water; (6) at times of low water levels, the wastewaters from surrounding settlements and from industry endanger the river water quality.

Based on the problems mentioned so far, a decision was made to develop a plan for the realization of a complex water-resources solution for the next 20-year period. This solution would meet the water demand of the population and industry as well as the needs of fishing and agriculture in a rational manner. It would also ensure the rational water-quality control of both surface and ground waters and ensure flood control regardless of whether the high water levels were due to surface or ground waters.

All the plans relevant to the realization of the complex water-resources system of the Cesma were completed using the methodology mentioned earlier and the procedure shown in Fig. 3. An analysis was done of all the available water resources in the entire basin. Other information included the water demand of all the consumers; the required level of water protection and protection against the adverse impact of water at the present time; and the planned economic, urban, and demographic development of the area within the next 20-year period. Finally, based on the topography and geology of the terrain as well as direct field observations, 49 locations were chosen as possible sites of future dams and reservoirs that would be used for regulating the waters in the area and for water-supply purposes. An analysis was also done of the cost of construction and of the cost of moving the people out of the area and buying their land and the structures on it.

After this preparatory work, it was possible to move on to the four phases of the procedure used for selecting the optimal water-resources solution.

Phase 1

In this phase an analysis was done of the optimal possible discharges from all 49 registered reservoirs as a function of the storage capacity. The analysis was done using the algorithms already mentioned in this paper. The effect of these reservoirs on flood reduction in the low-lying areas located downstream was also analyzed. It was concluded that this effect was minimal because the reservoirs are located far from the flood-damage centers and because they have a fairly small storage capacity.

Phase 2

Based on the analyses done in phase 1 and the shape of the basin, the distribution of the consumers, and the topography of the terrain, the basin area was divided into 17 subsystems. By applying the known procedure, an analysis was done to determine whether the available water could meet the demands of a certain subsystem or even those of a neighboring subsystem.

Phase 3

Based on the computations and analyses done in phase 2, alternative solutions were developed for each of the 17 subsystems, depending on the extent to which the water demand could be satisfied with a different number of reservoirs of different capacities.

For the sake of giving an example, 20 alternative solutions were developed for subsystem 11. Each alternative included several dams and reservoirs that could be built in a subbasin.

In choosing the best alternative solution, the following four criteria were also considered:

1. The rational use of water resources at the locations of the future reservoirs, to be achieved by formulating the degree of water use:

$$\min b = \frac{\sum V_d}{\sum V_{inf}} \qquad (10)$$

where $\sum V_d$ = amount of water distributed to consumers; and $\sum V_{inf}$ = inflow into the reservoir.

2. Impact on the environment evaluated through the guaranteed flow discharged downstream from the reservoir while meeting the water demand of all the consumers.

3. The water quality of the available waters, defined as a function of the depth of the water in the reservoir and the quality of the water flowing into it.

4. The social impact, based on the number of homes threatened because of the construction of the dam and the number of homes that need to be moved off the land for the future reservoir.

Based on the criteria functions defined in this manner, it was possible to compute the concrete values given in Table 1.

All 20 alternative solutions were ranked based on these criteria using iterative compromise programming (IKOR program).

The computations were also done for nine combinations of the weighting factor W and for two decision-making strategies (V_1) (Tables 2 and 3). Based on the performed analyses, it can be concluded that alternative 10, which includes three reservoirs, represents the best solution for subsystem 11.

All the other subsystems were analyzed in a similar way.

TABLE 1. Value of Criteria Functions for Different Alternatives—Subsystem 11

	Criteria Function				
Alternative number (1)	F1—investment (10^3 dinars) (2)	F2—degree of use (3)	F3—environmental impact (l/s) (4)	F4 Water-quality score (5)	F5 Social impact (number of lost dwellings) (6)
1	5,585	0.819	55	3.7	36
2	5,501	0.819	55	3.5	34
3	5,625	0.859	55	3.5	36
4	5,619	0.859	55	3.7	34
5	5,553	0.857	55	3.5	34
6	5,488	0.843	55	3.0	32
7	5,625	0.870	55	3.7	34
8	5,591	0.869	55	3.5	34
9	5,040	0.905	41	4.5	11
10	4,950	0.905	41	4.3	9
11	6,022	0.807	55	3.8	36
12	5,938	0.807	55	3.8	34
13	6,035	0.848	55	4.0	36
14	5,981	0.850	55	4.2	34
15	5,979	0.850	55	3.8	34
16	5,903	0.835	55	3.8	32
17	6,062	0.863	55	4.2	34
18	6,020	0.864	55	4.0	34
19	5,494	0.899	41	4.8	11
20	5,403	0.899	41	4.8	9
Optimization criterion	Minimum	Maximum	Maximum	Maximum	Minimum

TABLE 2. Weighting-Factor Combinations for Different Criteria—Subsystem 11

Criteria combination (1)	$W(kr)$ 1 (2)	2 (3)	3 (4)	4 (5)	5 (6)
a	1	1	1	1	1
b	2	1	1	1	1
c	2	2	1	1	1
d	2	2	3	1	3
e	3	2	1	3	2
f	1	3	3	3	2
g	4	3	2	1	2
h	3	2	1	1	3
i	2	1	3	3	3

TABLE 3. Ranking Lists for Implementation of Decision Strategy ($V1$) and Different Weighting Factors

Criteria combination (1)	$W(kr)$ 1 (2)	2 (3)	3 (4)	4 (5)	5 (6)	6 (7)	7 (8)	8 (9)	9 (10)	10 (11)
(*a*) Ranking for $V1 = 0.300$										
a	16	7	8	4	5	15	18	20	9	10
b	10	9	20	19	8	5	7	4	6	2
c	10	9	20	19	7	8	5	4	3	18
d	6	16	7	8	10	9	20	19	4	18
e	10	9	20	19	7	4	1	16	12	5
f	17	7	18	4	8	14	15	20	19	9
g	10	9	20	19	8	5	6	7	2	1
h	10	9	20	19	6	7	16	4	8	2
i	16	7	17	14	4	18	20	9	10	19
(*b*) Ranking for $V1 = 0.600$										
a	10	9	20	19	7	8	6	4	16	14
b	10	9	20	19	7	8	5	4	6	2
c	10	9	20	19	6	8	5	4	3	7
d	6	10	9	20	19	16	7	8	4	18
e	10	9	20	19	7	4	8	5	2	6
f	17	7	18	4	8	20	9	19	14	10
g	10	9	20	19	8	7	5	6	4	2
h	10	9	20	19	6	7	8	4	16	2
i	10	9	20	19	16	14	17	7	18	12

Phase 4

Using the multicriteria analyses done in phase 3, it was possible to develop a system of the most suitable solutions for each subsystem, which could also meet the water demands of a neighboring subsystem and of other subsystems located downstream.

Based on the results obtained in phase 3 of this procedure and analyses of the possible interaction between the neighboring subsystems and those

TABLE 4. Recommended Reservoirs

Subsystem (1)	Reservoir (2)	$W(k)$ (10^6 m^3) (3)	$W(mp)$ (10^6 m^3) (4)	$W(uk)$ (10^6 m^3) (5)	F ha (6)	Fish farm (7)	Guaranteed flow (m^3/s) (8)	Water supply (m^3/s) (9)	Irrigation areas (10)	Communities supplied (11)
1	3	3.84	0.144	7.25	920	1	0.016	—	F22, F24, F28, F29, F30	—
2	6	1.48	0.063	3.3	710	—	0.01	—	F17, F20, F21	—
3	9	2.12	0.061	3.7	1,010	—	0.012	—	F16, F18, F19	—
4	12	3.42	0.253	6.25	1,170	2	0.018	—	F13, F14	—
9	24	1.45	0.22	3.65	510	3	0.016	—	F7, F9L, F10, F11	—
10	30	2.85	0.19	5.7	1,070	4	0.014	0.0105	F23, F25, F26	1, 2
11	34	2.04	0.063	3.56	—	5	0.008	0.0042	—	3
11	35	5.63	0.006	10.8	230	6	0.018	0.0089	F15	4, 5
11	39	2.98	0.01	5.2	—	7	0.015	—	—	—
12	42	0.51	0.052	1.2	—	—	0.008	0.022/0.008	—	6
14	44	2.79	0.026	6	1,030	—	0.022	0.063/0.030	F2, F3, F4, F5	7, 8, 9, 10, 11
16	47	1.52	0.052	2.13	250	8	0.007	—	F1	—

downstream, alternative solutions were developed for several neighboring subsystems.

In this way it was possible to develop a greater number of alternatives that included several subsystems. To rank and choose the best alternative solution at this level, the IKOR program was used again and the criteria functions were defined as described in phase 3. It was thus possible in this phase to select the best alternative solutions for the wider area of the basin—in other words, aggregate the subsystems into a complex water-resources system that would in the best possible manner solve the problems defined at the beginning of the paper. In short, the available water resources (the available quality, quantity, and location) are transformed into

$$Q_R\, K_R\, L_R \rightarrow Q_p\, K_p\, L_p \quad \text{(11)}$$

which is the required water resource. The recommended solution, i.e., reservoirs for the entire basin, are given in Table 4.

Conclusions

The planning and management of complex water-resources systems is a very complex and responsible job, especially in developing countries. It requires the very careful study and analysis of all problems that could in any way affect the decision-making process.

To develop good quality plans for the development and management of water-resources systems, it is essential to:

- Study carefully and define the structure of the objectives that need to be realized by planning and managing a water-resources system.
- Investigate the available water resources in a basin area and define the water-quantity and water-quality time series.
- Analyze carefully and define the water demand and the need for water protection and protection against the adverse impact of water, all based on the physical and economic development plans made for the period of time for which the water-resources system is planned. If possible, the needs should be defined in the form of two or three alternatives (maximum, minimum, or mean).
- Analyze carefully all the possible alternative solutions that are important for the management and use of waters, to ensure water protection and protection against the adverse impact of water, and select the most suitable solution taking into consideration both the individual and common interests of the different users in the basin.

To plan and develop an optimal water-resources development plan, we recommend the systems approach using the multiple-phase optimizaton procedure, which includes the use of a system of models and procedures that make it possible to view the parameters of the system that can influence the choice of the best solution and the final decision.

The use of the multiple-phase optimization procedure is not directly related to the application of the specific mathematical models and programs that were mentioned in this paper (UMAX and IKOR compromise programming). This procedure should be viewed primarily as a philosophical approach to the definition of the optimal solution. In actual practice it is important to use the mathematical models and procedures that best suit the problem that needs to be solved.

Appendix. References

Biswas, A. K. (1976). *Systems approach to water management*. McGraw-Hill, New York, N.Y.

Duckstein, L., and Opricovic, S. (1980). "Multiobjective optimization in river basin development." *Water Resour. Res.*, 16(1).

Falkenmark, M., and Lind, G. (1976). *Water for starving world*. Westview Press, Boulder, Colo.

Goicoechea, A., Hansen, D. R., and Duckstein, L. (1982). *Multiobjective decision analysis with engineering and business applications*. John Wiley & Sons, New York, N.Y.

Freimer, M., and Yu, P. L. (1976). "Some new results on compromise solutions for group decision problems." *Mgmt. Sci.*, 22(6), 688–693.

Guidelines for evaluation of multipurpose water resources systems. (1985). Organization for Economic Cooperation and Development, Paris, France.

Haimes, Y. Y. (1977). *Hierarchical analysis of water resources systems*. McGraw-Hill, New York, N.Y.

Hall, W., and Dracup, J. (1970). *Water resources systems engineering*. McGraw-Hill, New York, N.Y.

Loucks, D. P., Stedinger, J. R., and Haith, Z. A. (1981). *Water resources planning and analysis*. Prentice-Hall Inc., New York, N.Y.

Major, D. C., and Zenton, R. Z. (1979). *Applied water resources systems planning*. Prentice-Hall Inc., New York, N.Y.

Management of water projects, decision making and investment appraisal. (1985). Organization for Economic Cooperation and Development, Paris, France.

Miloradov, M., and Opricovic, S. (1982). "Multipurpose water resources planning: The multi stage optimization." *Environmental systems analysis and management*, S. Rinaldi, ed., North Holland, Amsterdam, The Netherlands, 377–389.

Miloradov, M., and Simonovic, S. (1985). "Water resources and physical planning." *Proc. 8th Meeting*, Yugoslav Society for Physical Planning, Dubrovnik, Yugoslavia (in Serbo-Croatian).

Miloradov, M., and Tomanic, M. (1986). *Water resources master plan for the drava and the Danube in the SR of Croatia*. Inst. for Water Resour., Belgrade, Yugoslavia (in Serbo-Croatian).

Miloradov, M., Tomanic, M., and Opricovic, S. (1990). *Multicriteria analysis of multipurpose water resources systems*. Civ. Engrg. Dept., Univ. of Manitoba, Winnipeg, Manitoba, Canada, 637–647.

Miloradov, M., Opricovic, S., and Simonovic, S. (1986). *Water resources management and planning*. Inst. for Water Resour., Belgrade, Yugoslavia.

Opricovic, S. (1986). *Multicriteria ranking of alternative water resources solutions*. Naucna Knjiga, Belgrade, Yugoslavia (in Serbo-Croatian).

Opricovic, S., and Djordjevic, B. (1986). "Compromise ranking of water resources alternatives." *Proc. Symp. on Decision Making in Water Resour. Plng.*, Oslo, Norway.

Tomanic, M., Miloradov, M., and Opricovic, S. (1988). "Multicriteria planning of the river Drava water resources system." *Proc. 6th IWRA World Congress on Water Resour.*, International Water Resources Association, Ottawa, Ontario, Canada.