Use of simulation models in water resources systems analysis

D. N. KOROBOVA & V. I. POIZNER
Water Problems Institute, USSR Academy of Sciences, Moscow, USSR

ABSTRACT This paper discusses the state of the art in methods of solving problems of water resources systems management. It is shown that the method of numerical simulation is most effective in the analysis of water resources systems behaviour. Peculiarities of its use caused by the particular nature of the water resources systems are discussed. The application of this method to the study and analysis of hydrological forecasts used for water resources systems management is shown.

INTRODUCTION

The increasing water demand for economic development, on the one hand, and the necessity of environmental control including water control, on the other, makes the problem of water management one of the most urgent tasks of today. To solve this problem it is essential to develop large-scale water resources systems.

Water resources systems

The term "water resources systems" comprises water sources, means of their control and transportation to water users.

Though water resources systems have many common features with all large-scale national economic systems (e.g. transport, power production, etc.), they differ from them to some extent due to a number of peculiarities. One of them, variability of a river runoff, causes the stochastic character of processes connected with the selection of parameters of water resources systems and their operational rules.

Water consumption is also stochastic. This is determined by fluctuations of precipitation, processes of soil formation, solar activity in agriculture, biogenic flows in fishery, etc. Moreover, other unknown or uncertain factors of a technical and economic character may also be of considerable importance.

Therefore, to solve the problem of water supply to the national economy, one must analyse the problem of coordination between stochastic water resources and the demand in them. The main way of tackling the problem is the redistribution of water resources in time by runoff regulation and in space by interbasin and interregional water transfer.

River regulation by reservoirs

Reservoirs are clearly the main element of water resources systems;
characteristics of their design and operation form the basis for the theory of runoff regulation developed in the USSR mainly by Kritskii & Menkel (1952).

The theory of runoff regulation provides a means of establishing relationships between three important parameters of a water resources system: usable storage of a reservoir (β); its yield, or water supplied to users (α); and the reliability of water supply or probability of exceedance (p).

To maintain control over the above parameters in real time operation, runoff regulation must be carried out in accordance with some rules, which incorporate conditions of water utilization and real hydrological information. These rules are based on the principle of "dispatching" of water resources systems regimes. This principle means that water supply (α) from a reservoir is defined by content and time as a characteristic of runoff distribution and water utilization. The principle of "dispatching" can be expressed in different ways. In the USSR, dispatcher rules are traditionally used. They allow one to define zones of reservoir storage which are associated with various purposes. Besides, in the USSR and in other countries, systems of priorities are widely used. These systems determine the order and degree of water limitations according to the importance of water users and the water abundance of the period. The desire to maximize the degree of runoff utilization necessitates attempts to use long-term forecasts for operational aims from a number of months to a year ahead (Velikanov & Poizner, 1980).

Runoff forecasting and risk

The probabilistic nature of long-term forecasts implies a risk of taking the wrong decision when the forecast is wrong. Recent studies show that the desire to maximize the utilization of runoff inevitably contradicts the necessity to maintain some definite guarantees of water supply reliability. Real operational rules are aimed at a compromise between the two aims. The relation between them is defined on the basis of trade-offs between the economic effect from the rise in the degree of water utilization and damages from diminishing water supply reliability.

Ecological aspects

Considering comprehensive conditions of water resources systems designing and functioning, the constant growth of water utilization should be noted especially in agriculture, which has already caused an appreciable deficit of water in some regions of the world. The consequent effects on the quality of fresh water must be taken into account in public and industrial water supply. The problem of water pollution as a result of human activities has not only a technological aspect, but also an ecological one as it threatens the stability of the fresh water ecosystem.

The ecological aspect appears in the disturbance of seasonal water distribution and in the growth of unproductive water losses as a result of runoff regulation by reservoirs. This is especially important, when the interaction of rivers with inland seas and lakes can allow the effects of regulation in one river to influence the
biota of all connected systems.

DEVELOPMENT OF OPERATING POLICIES

All these factors must be considered in the operational policies of water resources systems. At the planning stage, operating rules allow one to explore system performance and estimate its technical capacity and environmental impact. At the operational stage, the rules provide a way to maintain the firm yield of the system or, when the projected conditions are changed, to correct the regime of the system.

The analysis of these tasks must be based on the use of modern mathematical methods and computers. It should be noted that many resources problems have been solved with optimization techniques. The adequate mathematical development of these techniques and the possibility of their numerical realization on computers allows us to use them widely in studies in hydropower engineering.

Optimization techniques

Some essential difficulties in utilization of optimization techniques arise, however, due to the increasing complexity of water resources systems. These difficulties are caused by the lack of reliable economic information on the components of the system and by the absence of cost characteristics of damages for some components, which are necessary in optimization of the system operation in deficit water periods.

The above reasons make it necessary to formulate the processes of water resources systems design and operation as ones of multi-criterion optimization, that cannot be solved directly. It should also be noted that, when optimization techniques are used to analyse these processes for large-scale systems with complex internal and external connections, considerable simplifications of a formal picture of the system are made (i.e. linearization of characteristics, simplification of operation, an increase in estimated time spans). The decisions, made in keeping with this approach, are rather inaccurate and, therefore, they cannot be used in water resources practice.

An analysis of experience of mathematical programming methods, used to optimise the parameters and the regime of water resources systems, shows that they can be used successfully in solving large-scale regional tasks or some particular tasks (usually operational ones) which can be formulated in terms of one criterion. The methods are helpful also to establish the range of permissible decisions of multicriterion optimization tasks.

Therefore, we can state that it is impossible to create optimal rules of water resources systems management with the use of mathematical programming alone. Those studying other large-scale systems have also encountered the same difficulties. The only solution of this problem is active participation in all stages of data analysis and decision-making.
Numerical simulation techniques

For reasons given above there is increasing use of simulation modelling for study and analysis of water resources tasks. Simulation modelling opens up a wide range of possibilities for investigation of the large-scale water resources systems behaviour by combining the memory and speed of computers with the flexibility and judgement of the human intellect. The ability of decision-making to find a compromise between different demands and to find satisfactory conditions in the vector space of system conditions is of crucial importance.

The use of the methodology of operational research, based on active man-machine dialogue can, even within the model being used, give a new character qualitatively to system development. Analysing the obtained results, a decision maker learns more about the peculiarities of the structure of the system and the character of possible change of its main parameters. Therefore, simulation modelling allows a specialist to consider the whole range of possible operating effects and guarantees purposeful research, which leads to the required development of the system. Such a conclusion stresses the necessity for the most serious attitude towards the representation of operational processes in simulation models, which are used for studying large-scale water resources systems functioning.

There are different approaches to the development of a model for simulation in different theoretical and applied branches of science. When analysing the above mentioned processes, it is customary to use the given theory and practice of water resources calculations, which can be viewed as a formalized reflection of the process of water resources functioning (Korobova & Poizner, 1978).

USE OF SIMULATION MODELS: A CASE STUDY

In the USSR, a set of simulation models used for the analysis of water resources systems with one reservoir or a group of them under different operational conditions have been constructed. Such models allow one to estimate the influence of different operational factors on these regimes. It is important to estimate the efficiency of using long-term hydrological forecasts as an integral part of a set of operating rules. This has been done by a series of experiments using a simulation model of a water resources system with one reservoir and many water users, some of which can utilize water surpluses. A technique has been developed to conduct simulation experiments for estimation of the efficiency of different operational factors. This technique is based on the principle of creation of a zone of possible operation and localization of regimes under study (Velikanov & Poizner, 1978). Some regimes are analysed in order to create the zone of possible operation of a simulation model. They show extreme operational strategies, i.e. regimes of maximum possible maintenance of guaranteed supply (firm yield) and regimes of maximum possible runoff utilization. In the first case, the guaranteed supply is maintained in all the volume of regulation, the rise up to a maximum value being possible only when the
reservoir is full and there are runoff surpluses. On the contrary, in the second case the maximum possible output for each water user is maintained in all the volume of regulation. When the level of the reservoir is lowered to a dead volume, the supply depletes to zero, and the water resources deficit is fixed. The reliability indices and the mean annual values of deficits and discharges are used as indices of the efficiency of the system's functioning. A water deficit is defined as an average volume of water for a number of years which is insufficient to maintain the guaranteed water supply.

The reliability indices in the studied regimes will have extreme values, i.e. (a) the reliability of firm yield is maximum for the guaranteed regime and minimum for the regime of maximum runoff utilization; (b) the volume of deficit for the guaranteed regime is minimum, for the regime of maximum runoff utilization it is maximum; (c) the volume of spills is maximum for the guaranteed regime and minimum for the regime of maximum runoff utilization.

These two extreme regimes provide a way to create the so-called "standard" regime of runoff regulation prediction. In this case, runoff prediction is used for all the period of regulation. The standard regime is an optimum variant of operation. Spills and damages occurring in this regime at this level of water consumption cannot be eliminated by any operation action.

All regimes under investigation are located in the sphere of possible operation indices. After this, an additional analysis, which takes into account the specific peculiarities of the system, can be made.

The proposed technique has been used for the efficiency analysis of operation of releases, for fishery purposes, from the Tsymlyansko Reservoir on the River Don. Factors affecting operating rules are the existing storage in a reservoir at the time of decision-making and a predicted value of the volume of water flow to a reservoir during the spring flood.

A probabilistic mathematical model has been used to define the predicted runoff, based on the composition of a three-parameter gamma distribution for runoff volume and a normal distribution for the error of forecasts. Let the random value \( x = \Delta \), an error of forecast, have a standardized (zero mean, standard deviation equal to unity) normal distribution with probability density function:

\[
P_1(x) = \frac{1}{\sqrt{2\pi}} \exp(-x^2/2)
\]

and let the random value \( y = W_{\text{for}} \), a forecasted supply (inflow) have a three parameters gamma distribution with parameters \( y_0, \gamma, b \) and probability density (Stacy & Mihram, 1965):

\[
P_2(y) = \left[ \frac{\Gamma(\gamma + b)}{\Gamma(\gamma)} \right]^{y/b} \frac{1}{\Gamma(\gamma)b/y_0} \frac{y}{y_0}^{(\gamma/b)-1} \exp\left[ -\frac{y}{y_0} \frac{\Gamma(\gamma + b)}{\Gamma(\gamma)} \right]^{1/b}
\]

then the density of their joint distribution can be expressed as

\[
\psi_1(x, y) = P_1(x)P_2(y)\{1 + 6\lambda\phi(x) [2P_2(y)dy - 1] + 5\lambda^2 [6\phi^2(x) - \frac{1}{2}] [6P_2(y)dy]^2 - 6P_2(y)dy + 1\}
\]
where $\lambda$ is the coefficient of correlation between the probabilities of exceedance and $\phi(x)$ is the probability integral. The conditional density of the error distribution of a forecast $x$ with the predicted runoff $y$ is

$$\psi_2(x|y) = P_1(x)\{1 + 6\lambda\phi(x)[2F_2(x) - 1]\} + 5\lambda^2[6\phi^2(x) - \frac{1}{2}] \times \left[6F_2^2(y) - 6F_2(y) + 1\right]$$

(4)

where $F_2(y)$ is the preset value of the function of the three-parameter gamma distribution.

The conditional expectation of distribution (4) is equal to

$$M_{1,0}(y) = \frac{3\lambda}{\sqrt{2\pi}}[2F_2(y) - 1]$$

(5)

and the conditional dispersion is

$$\sigma_x^2(y) = 1 - \frac{5\sqrt{3}}{2\pi} \lambda^2 + \frac{15\sqrt{3} - 18}{2\pi} \lambda[2F_2(y) - 1]^2$$

(6)

This analysis shows that, when $x \leq 0.5$, the distribution (4) can be acceptably approximated by a normal distribution, given the limited exactness of definitions of hydrological characteristics. Therefore, the conditional distribution of errors of forecasts can be considered normal with parameters defined in (5) and (6).

Simulation experiments designed to evaluate the efficiency of using hydrological forecasts in operational conditions have been conducted for a conditional average predicted runoff defined in (3) and with quantiles of 10%, 25%, 75% and 90% reliability of a conditional curve of errors of forecasts. Table 1 gives the results of these experiments.

As the table shows, the operating rules provide a means of varying the regime of water resources systems widely. An analysis of the results allows us to conclude that the neglect of the stochastic essence of hydrological forecasts lead either to a definite rise in the projected water resources characteristics (regime 4 in the table, where forecasted inflows are equal to actual ones) or to irrational use of operational possibilities of a reservoir (regime 5 in which a release is determined by the level of a reservoir only, and runoff is considered to be equal to its unconditional average). Further analysis of Table 1 (variants 6-10) and also an additional analysis allow us to give recommendations concerning the reliability of hydrological forecasts, which can be used to determine fishery releases.

CONCLUSION

With the growing complexity of hydrological calculations, and the many conflicting criteria, of water resources systems it will be more and more difficult to select optimum control procedures. Under these conditions the formal use of mathematical programming methods (i.e. objective optimization) will lead to unsuitable results for water resources systems. The use of the method of numerical simulation for this purpose can turn out to be more effective than optimization.
### TABLE 1  Results of simulation experiments

<table>
<thead>
<tr>
<th>Nos</th>
<th>Regime characteristics</th>
<th>Probability of firm yield to water resources systems components (%)</th>
<th>Probability of maximal ecological release (%)</th>
<th>Average multiyear ecological deficit (10^6,m^3)</th>
<th>Average multiyear discharge (10^6,m^3)</th>
<th>Runoff use coefficient (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Guaranteed</td>
<td>96.4 94.5 96.4</td>
<td>42.6</td>
<td>0.08</td>
<td>4.7</td>
<td>79.0</td>
</tr>
<tr>
<td>2</td>
<td>Maximum runoff use</td>
<td>38.9 38.9 80.4</td>
<td>64.8</td>
<td>2.45</td>
<td>1.3</td>
<td>94.0</td>
</tr>
<tr>
<td>3</td>
<td>Standard</td>
<td>96.4 94.5 96.4</td>
<td>27.8</td>
<td>0.08</td>
<td>1.3</td>
<td>94.0</td>
</tr>
<tr>
<td>4</td>
<td>Absolutely correct</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>forecast</td>
<td>85.5 83.6 90.7</td>
<td>27.8</td>
<td>0.28</td>
<td>2.3</td>
<td>89.9</td>
</tr>
<tr>
<td>5</td>
<td>No forecast</td>
<td>64.8 64.8 83.3</td>
<td>24.1</td>
<td>0.74</td>
<td>2.8</td>
<td>87.6</td>
</tr>
<tr>
<td>6</td>
<td>Forecast P = 10%</td>
<td>66.7 66.7 83.3</td>
<td>27.8</td>
<td>0.64</td>
<td>2.3</td>
<td>89.8</td>
</tr>
<tr>
<td>7</td>
<td>Forecast P = 25%</td>
<td>72.2 72.2 85.2</td>
<td>25.9</td>
<td>0.52</td>
<td>2.4</td>
<td>89.2</td>
</tr>
<tr>
<td>8</td>
<td>Forecast conditional</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>average</td>
<td>75.9 75.9 87.0</td>
<td>25.9</td>
<td>0.43</td>
<td>2.6</td>
<td>88.5</td>
</tr>
<tr>
<td>9</td>
<td>Forecast P = 75%</td>
<td>81.5 81.5 90.7</td>
<td>22.2</td>
<td>0.33</td>
<td>3.1</td>
<td>86.3</td>
</tr>
<tr>
<td>10</td>
<td>Forecast P = 90%</td>
<td>85.2 85.2 85.2</td>
<td>22.2</td>
<td>0.30</td>
<td>3.5</td>
<td>84.5</td>
</tr>
</tbody>
</table>
techniques either in the scientific study or in the design of water resources systems.

REFERENCES


