Decision-support systems for water management

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Abstract

Decision-making processes in water management are characterized by a typical hierarchical structure and a high degree of complexity. Complexity and the relevance of these problems for water management and for the national economy make the application of efficient methods and models as decision-support systems for rational and effective decision making indispensable. All these components were taken into consideration in the development of the computer-aided system of water management in the Spree river basin, German Democratic Republic (GDR). A brief description of the entire system is followed by a more detailed presentation of two important system components: the decision-support system MINE serving for the analysis of water management strategies in the areas of open-cast lignite mining, and the decision-support system REHSPROX/SPROXEC for the operation and development of wastewater treatment plants. Finally, the paper deals with practical experiences in connecting research and practice in the development and implementation of the system.

Decision-Support Systems (DSS) as Components of Computer-Aided Water Management

Because of the complex interactions between human society and water resource systems, as well as the rapidly increasing intensity in the use of water resources, many countries face the task of achieving a higher level in water management planning, in the management and protection of water resources, and in the control of ongoing hydrological processes. This pre-supposes both the creation of improved methods and models and the qualification of decision-making processes and decision makers.

A comprehensive and detailed analysis of the availability of water resources in terms of quantity and quality, and of water demand in their variability in space and time, is indispensable. This analysis has to take into consideration all anthropogenic impacts on the water resource system, and the conditions and consequences of measures of rational utilization of water and water protection, while keeping in mind the present and future demands of human society.

Under the specific conditions of hydrology and water utilization in the GDR, this task assumes special importance. For instance, the available water resources amount, on average, is a mere 450 m³ per inhabitant per year. This is about one-quarter of the European average. In dry-weather years, water demand exceeds available supply, so reuse of water resources becomes a necessity. This is why systems for computer-aided management of river basins and supply areas increasingly are being developed and implemented in practice.
The development of a system for computer-aided management in the Spree river basin, the major resource of water supply in the Berlin region, resulted in a basic structure as shown in Fig. 1. This structure proved to be appropriate and can be characterized by the following main components:

(a) measuring and information systems (data acquisition, transmission and storage), including the measuring and transmission equipment;

(b) software system (user software); and

(c) organization system (organizational structure, legal and economic regulations).

In developing and implementing such systems, three typical scopes and respective decision levels with strongly differing time horizons must be distinguished:

(a) planning tasks relating to the planning of the structural development in longer time horizons (usually more than 20 years) and for the dimensioning of water management systems;

(b) management tasks for the long- and medium-term management of water resources in a given water management system with a defined structure for time horizons of several years; and

(c) operational forecasting and control tasks for real-time control of processes in water management systems (time horizons ranging from hours and weeks to months).

Each of these three main tasks are considered in the overall system shown in Fig. 1. It is obvious that the significance of the various components varies with the tasks. For operational control the problems of data acquisition and transmission are in the foreground. The focus shifts with growing time horizons needed for management and planning towards the software system and determination of national economic requirements. At the same time, the uncertainty of the information to be processed increases just like the subjective element in decision making, which cannot be described completely by models. Accordingly, the software systems to be developed are not decision-making, but decision-supporting systems, i.e. their job is not to supply the decision maker with an optimal solution, but to provide tools that ensure rational decision making.

Two components of the computer-aided system of water management in the Spree river basin that meet this demand are presented below. The operational hydrological component of the system is treated in a paper by Becker et al. (1989).

**Decision-Support System REHSPROX-SPROXEC**

Along the upper course of River Spree, multiple processes of water uses in municipalities and light industries overlap each other within a very narrow space. Water quality has to be preserved under consideration of growing demands of water users to such an extent that all multiple user requirements in the region and down to the Berlin area can be met. Of major significance is the maintenance of the self-purification capacity in the water body.
Fig. 1. Components of the decision-support system used to assist operators, managers and planners.
Typical decision problems are the development and mode of operation of wastewater treatment plants. Decisive criteria for the self-purification capacity and the organic pollution load are oxygen content and BOD\textsubscript{5}. The developed decision-support systems are based on the following components (see also, Gnauck et al., 1988):

(a) the programme system REH (computer-aided decision aid for multi-criteria decisions), developed by the Central Institute of Cybernetics and Information Processes of the GDR Academy of Sciences;

(b) the self-purification model SPROUX (a modified Streeter-Phelps model), developed by the Institute of Water Management.

The model system REHSROUX ensures a Pareto-optimal control of existing treatment plants. The model concept is shown in Fig. 2. The water body is discretized in segments; state parameters are oxygen content, BOD\textsubscript{5} and discharge per segment. The control parameter is the volumetric flow of point-source discharges of treatment plant effluents. The target functions are: (a) maximizing the mean oxygen content (\(\geq 6\text{ mg/l}\)); (b) minimizing the mean BOD\textsubscript{5} concentration (\(< = 10\text{ mg/l}\)); and (c) maximizing the amount of wastewater discharged. The maximum admissible values given in parentheses are those of the GDR National Standard "Classification of Flowing Waters" (TGL 22764) for quality class 2.

The model enables the user to:

(a) analyze the effects of all point-source omissions of organic pollutants (related to BOD\textsubscript{5}) in all segments simultaneously for any control variant and to determine their impacts on the oxygen content along the longitudinal section of the river;

(b) select from the variety of control alternatives the Pareto-optimal one (compromise solution);

(c) compute for every point the control variant corresponding to the compromise solution (BOD\textsubscript{5} concentration, effluent quantity, \(O_2\) content) for all segments and time steps; and

(d) perform control computations under consideration of given conditioned preferences.

The REHSROUX model is run segment-by-segment with the computed Pareto-optimal controls of the i-th segment serving as initial values for the (i+1)-th segment. Fig. 3 shows the compromise solutions for different control variants.

The SPROUX model was used to find Pareto-optimal solutions for the development and construction of wastewater treatment plants. Here, the target function "Maximizing the amount of wastewater discharged" was replaced by the target function "Minimizing investment costs."

The control parameters were discrete variants of the construction stages of the treatment plants (according to the applicable national norms and technical parameters). The computation results are those combinations of treatment plants in the river basin and the
PARETO - optimal Control by REHSPROX Models

Waste water input
control - | uncon- able | trolled
Sewage | Tributary
treatment | creek
plant | run-off

Fig. 2. Schematic of optimal control system and models.

Fig. 3. Compromise solutions for different control variants.
respective segment that belong to a compromise solution and the state parameters of the water body resulting therefrom.

Decision-Support System MINE

The decision-support system MINE was developed at the International Institute for Applied Systems Analysis (IIASA) in Austria in cooperation with the Institute of Water Management, GDR, and other institutes in the GDR and Poland. Its purpose is the analysis of regional policies of water management in lignite mining areas. A more detailed description is given in Kaden et al. (1986) and Orlovski, Kaden and Walsum (1986).

In order to highlight the impacts of lignite mining in the GDR, it should be mentioned that presently more than 1.800 million m$^3$ of water per year are pumped in order to dewater the open-cast mines. This figure corresponds to about 20% of the stable runoff of the whole country.

The test region considered is the eastern Lusatian Lignite District, which is located in the basin of River Spree. Here, lignite mining has a dominating influence on the runoff processes in surface waters -- both through significant discharges of open-cast mine drainage and the significant seepage losses from the surface waters into the widely lowered aquifers. Decisions of relevance for water management concern the use of remaining pits as reservoirs, the use of mine drainage for water supply or for stabilizing the discharge from the river, and the treatment of the acid iron-containing mine drainage.

The first level of the two-level model system is designed as a planning model for the analysis of fundamental decisions concerning management and technology, covering a relatively small number of planning periods. The planning horizon extends over 50 years and is divided into non-equidistant time steps between one and 15 years. Rational strategies of long-term systems development are determined by means of a dynamic multi-criteria analysis considering the number of specific criteria such as costs of water supply, costs of mine drainage, satisfaction of the water demand of different users, and environmental considerations. For the multi-criteria analysis, the reference-point approach is used. The resulting non-linear optimization problem is solved by an adequate problem solver (Kaden and Kreglewski, 1986).

The planning model is based on a number of more or less strong simplifications, such as:

(a) the discretization of the planning horizon into a small number of planning periods; e.g. decisions are assumed to remain constant during one planning period;

(b) the neglect of uncertainties in model inputs;

(c) the application of simplified sub-models obtained through reduction of comprehensive system-descriptive models.

That is why a second-level management model for the simulation of system behavior for a large number of shorter management periods (monthly and yearly time steps) was developed. It is used to analyze managerial decisions by means of stochastic simulation (Monte-Carlo method) and to evaluate the results obtained from the planning model.
The decision-support system that previously had been developed (until 1986) at IIASA is being extended and implemented in cooperation with potential users in the respective water authorities with a focus on the following aspects:

(a) Implementation of the system with hardware available to the model users (Water Management Authorities), i.e. the originally implemented VAX 11/780 system had to be transformed for IBM-XT compatible equipment. This job proved to be less problematic than expected. Good pre-conditions for the transformation were given by the modular development of the original system in FORTRAN 77. In order to reduce computation time, the original system, partially written in double precision, was transformed to single-precision programming throughout the system. The computation times are only insignificantly longer in comparison to a fully utilized VAX in multi-user mode. In any case, it was possible to maintain a reasonable response time to allow interactive operation of the model.

(b) It was necessary to increase the precision of the system regarding the control parameters, state parameters, and target function. The number of control parameters increased from some 30 to 45 for each of the ten planning periods. Fig. 4 depicts the extended system scheme for the application in eastern Lusatia.

(c) The system extension necessitated the development of new models for sub-processes. This applies both to the modeling of interactions between surface water and groundwater and, especially, to economic sub-models. However, the effort that had to be devoted to the development of these sub-models turned out to be considerable. Presently, the extended model version is in the test phase.

Closing the Gap Between Theory and Practice

The following sections summarize our experiences in establishing a closer link between research and practical application.

(a) The computer-aided system is now in routine operation at the responsible water authorities. A pre-condition for this success was the understanding of the necessity to employ modern computer-aided methods of water management for the solution of actual complex tasks on the side of those working in practice.

(b) The customers who ordered the research that was performed at the Institute of Water Management were the Water Management Authorities responsible for the region.

(c) The users were integrated into the process of research as much as possible in order to ensure a solution of the problem that fits the conditions in practice. Special importance was due to the user-friendly design of the program.

As mentioned above, the developed system is a system serving very different needs, ranging from operational control problems to water policy matters; from the simple to the complex. Naturally, the description given above has to be differentiated for each of these components.
Fig. 4. Extended system of water management in the Eastern Lusatia Lignite District.
It is beyond argument that the developed decision-support systems were of value to the Water Management Authorities. However, the products are not used by these authorities as a whole, but by their responsible senior staff. The acceptance a product finds will be directly proportional to how closely it relates with the duties of one (or several) of these officials. This fact clearly favors simple, well-limited solutions with high user-friendliness. Flood forecasting models, for instance, are readily accepted. They are even requested if they help to rationalize the daily routine work and increase the reliability and precision of forecasts. Accordingly, the statements above are unreservedly valid for the operational components of the developed system of computer-aided management.

The same is true for the developed models of long-term management (simulation models based on the Monte Carlo method) that are employed to find effective management strategies for reservoirs to substantiate long-term balance decisions (water-use permits). Here too, a clear "personal" relationship exists between model designer and user.

The more complex the models become, and the more they assume an interregional and intersectorial character, the more difficult it will be to define a typical user. The model content must consider the sphere of responsibility of the individual manager or official. Thus, the risk arises that the model may become the tool of a more or less "anonymous user" and will, consequently, find hardly any practical application. It is obvious that these aspects are particularly relevant for complex decision-support systems. The following essential experiences could be collected in the development of the systems described earlier.

(a) The decision makers who bear the responsibility for the scope of the decision-support system (as a rule, high-ranking senior staff and not the direct user/operator of the model) have to be convinced of the effectiveness of the developed systems. This can be achieved by demonstrating the system effectively in a posteriori simulations of earlier decisions by using representative display graphics, and by proving the intended effects of model application. This approach allows access to the level of the actual model user. Only so is it possible to conquer fields of application for decision-support systems outside their present scope. This claim can be corroborated by the experiences with the decision-support system MINE which played, and still plays (accompanied by high publicity), a pioneering role in the application of decision-support systems in water management in the GDR.

(b) It is essential to identify the actual model operators ("decision proposers"). As early as possible in the model development stage, mixed teams of researchers and users should be formed. This continuous dialogue between model designer and model user must result in a scientifically demanding and practical solution.

(c) Design models to be only as complicated as necessary for solving the given problem (and the required precision of the outputs). User-friendliness plays an important, but ultimately not the dominating role herein. Experience has shown that qualified model users do judge less the "appearance" of the model than its essential core. The same holds true for computer graphics. It must be shown that it has real functionality besides its representative character. Graphics must consistently support the actual decision preparation. Here, a growing integration of information mapping is granted essential importance.
The application of decision-support systems should be based on reasonable, well-defined problems. The more complicated the problem to be treated, the lower the practicality of the model. It goes without saying that the problem must not be so restrictive that it is deprived of all practical relevance. Obviously, the two systems described in this paper form the upper and lower limits in this sense. So, BOD$_C$ is an important criterion for the operation and designing of wastewater treatment facilities, but ultimately it is not the only decisive one (think of non-biodegradable organics). This means that REHSPROX/SPROXEC covers only one part of the decision field. In contrast, the MINE system, with its very complex approach, reaches up to the limits of technological feasibility and of the mental capacity of the users.

In developing decision-support systems on the basis of multi-criteria analysis, a reasonable limit should be set on the decision range. The simultaneous processing of more than two to five target functions exceeds the capacity of human perception. The user must be appropriately guided in the handling of the decision-support system. For alternative decisions, a standard alternative should always be programmed. This approach with the reference-point procedure in the MINE system has, without doubt, withstood the test (Wierzbicki, 1983) as it facilitates the consideration from the point of view of the engineer.

The development of complex decision-support systems is not a unique research task for a fixed period of time. In the phases of practical implementation and application, it needs a continuous adaptation to the changing external conditions and, at the same time, to the growing demands of the users (who become more and more aware of the potentials of the model). The research capacity for this must be planned and provided -- as the experiences gained in the application of the decision-support model MINE explicitly taught us.

**Outlook**

The use of decision-support models in water management is still in its infancy. With the attempt to bring these systems together as close as possible to the decision maker (proposer), it should become possible to bring together the subjective aspects of decision making with the objectives ones. In this sense, a future combination of decision-support systems (as a kind of algorithm-based expert systems) with the classical type of expert systems (based on factual knowledge) is considered to be the most adequate form of support of decision making in water management. Most of the technical prerequisites are available now, or will be in the not-too-distant future.

**References**


