13 PROSPECTS OF WATER RESOURCE SYSTEMS ANALYSIS AND SYNTHESIS

13.1 GENERAL ASSUMPTIONS OF THE SYSTEMS APPROACH IN WATER SCIENCE

The consequence of the economic, social and cultural development of mankind is the growth of requirements for the quantity and quality of water resources, their more intensive and comprehensive use. The unequal distribution of water resources capacity and water demands in time and place will require co-ordination of water management over ever increasing territories with a growing number of relationships between resources and users. The conflicts between different objectives of water resource development are likely to sharpen with the growing imbalance in supply and demand integration. The increasing dynamic rates of technological and economic changes will accelerate the dynamics of water management. The impacts of anthropological factors on the hydrological cycle, on quantitative and qualitative movement of water in nature, i.e., the feedback relationship between man and water resources will grow stronger. All these phenomena have a probabilistic nature, and their future behaviour cannot be predicted accurately.

The future development of water resource management, as outlined, shows that treatment of all its problems will require a dialectic approach that is, and will be, performed by the systems approach with the use of stochastic, heuristic and prognostic methods.

WRS design and operation will become a more comprehensive and more frequently used tool of water resources development studies. In spite of progress in science and technology and their working methods, it cannot be assumed that the WRS problems will be treated in all their complexity as they occur in nature and society. A purposeful simplifying abstraction will be necessary in the identification of the systems and their modelling in order to make them mathematically tractable and to offer results reflecting the real problems in such a way as to aid decision-making, design, construction and the operation of WRS.

Direct experiment with WRS, as compared with other systems, cannot be undertaken in view of high costs, operational and environmental consequences, the long-term function of its components, etc. These circumstances influence the prospects of the application of optimizing techniques of system modelling of this kind. Therefore, modelling of the optimal operation of WRS tends towards the application of mathematical models. The development of mathematical models of WRS is the main direction of scientific research of WRS.

The systems identified with complex and large-scale WRS are open systems – they have both inputs and outputs.

Hydrological and water quality data are among the most important input values. Therefore, systems hydrology should be developed to offer input variables for WRS, i.e., data with probability description and invariant characteristics in the future, which can be used to reflect the anthropological factors impact on uncontrolled hydrological conditions. Hydrology, too, is to be orientated prognostically rather than statistically as it has been up to now. Therefore, more attention should be given to the basic relationships in the mass balance equation, to the relationships between surface and ground water, evapotranspiration and changes in the human impact on the landscape and impact on the generic elements of the hydrological regime. The co-operation of hydrologists in research and design teams then becomes essential.

We believe that water quality requirements on WRS will grow faster than those of water quantity. The change of water quality, particularly in recent years, is a more dynamic element in WRS than its quantity. Despite measures for water pollution prevention the optimistic predictions have a relatively low reliability.

During recent years, sources of pollution that had been neglected grow in importance. It is difficult to control the point source of pollution and the sources of non-point pollution grow exponentially. The prospect of future development and search for effective technical and administration measures for water quality management are very important activities for the solution of WRS issues. In these considerations the problem of reliability cannot be overlooked; at present potential sources of pollution of enormous importance are emerging. Therefore, the point is not only operational reliability, but also reliability related to the risk of failure of WRS functions concerning water quality.

The boundary problems between the water quantity and water quality are formed by the quantity – quality relationships in water resources facilities. A start has been made in dealing with these relationships. Their importance is essential for WRS, and, therefore, research in the laboratory and under field conditions has to be accelerated.

All the problems discussed require an enormous research capacity, which cannot be carried by one country alone. International co-operation is necessary, and this is also the case for other WRS issues. This co-operation has been developed in the CMEA countries and also on a broader scale (IIASA, IWRA, etc.).

There are a number of methodological questions that have not yet been answered effectively. These questions concern the decision theory, the application of which is to be used for scientifically approved optimal decisions. The currently used optimization methods are often too "weak" for decision-making in complex WRS.

A further development of the theory of games and heuristic methods and their application will be necessary.

An important aspect of decision analysis is the reliability of systems. In spite of the fact that reliability is a classical notion in water management, its importance in application to WRS has often been reduced and simplified. A theory of risk and reliability, taking into account many aspects of WRS, has to be developed.

We are persuaded that a single algorithmic activity in WRS is often cumbersome and cannot hit the target. In this situation it is sometimes necessary to deviate from the algorithmic experience and use a shorter relationship between intuition and decision. It will be necessary to analyse methodologically the fact that man deals with most of his problems heuristically, i.e., he uses a method based on the development of inner models that are orientated towards a single clear purpose without superfluous complexity. Some indisputable advantages of heuristic methods, distinguished by creativity, are a sufficient impetus for more attention despite resistance on the part of certain "experienced" experts, who are not able to change their views due to accumulated, but one-sided experience. Correct, true and extensive is a component of qualification and it is indispensable in the verification of modern ideas.

A surviving phenomenon of skilled, but conservative activity, based on past experience, is the methodological approach based entirely on the past and frightened of uncertainty in the future. However, in a society which builds up its future on a scientifically elaborated plan, the necessity to create an image of the future world is essential, and prognostic rather than static aspects need to penetrate into all theories.

In WRS the prediction of the future state of water resources is an integral component of their design and operation. The extrapolation methods are very useful for prediction and often are, and will be, applied in water management, whatever other methods follow, which might reduce the danger of false trends and sources of errors inherent in it.

Further, in water management prediction it is often necessary to abandon mathematical and exact procedures, which do not entail the anticipation of a new mathematically unexpected reality – a discovery. Subjective methods involving imagination and brainstorming of properly chosen experts should be applied here.

WRS analysis and design is creative work. The interdisciplinary and large-scale character and novelty of the topic requires investigation and research by broad teams. Scientific knowledge should be used to set up creative teams, their style of work, with the right to use new approaches, including the risk of failure, the psychology of research teams, and the right to overcome administrative obstacles that hinder team work in WRS.

The most difficult prediction problems include the prediction of the future demands of WRS, as water management mostly serves other branches of the national economy and the development of society. Flood control and the municipal water supply are the most reliable components of this prediction. The water management administration has to intervene in all components of its system environment to gain relatively reliable predictions of their requirements on WRS dozens of years ahead of time. A necessary corollary is planning of budgetary and construction capacities to meet these requirements in place and time.

All these aspects of water management development have been concentrated in the General Water Plan of Czechoslovakia. Subsequent planning in economic and construction studies should incorporate the relatively fixed time schedules of WRS development. Unless this condition is met, WRS development will not be rational and the best WRS design and operation will not be able to attain the maximum possible benefits.

High initial costs and a long physical and economic life are a special feature of water management which has serious economic, environmental, and other impacts. The effort to express certain environmental effects and intangibles in economic terms can add homogeneity to comparisons of studies and alternative designs. The lack of reliable indices of economic effectivity in water management and, on the other hand, poor knowledge of loss functions due to water shortages are the weakest points of optimization computations. The organization of comprehensive collection and processing of various data concerning WRS operation is an integral part and assumption of a reliable economic basis of WRS and the whole water management sector.

Modelling WRS we are interested, in the first place, in the behaviour of the identified system; in the cybernetic models the structure of the system need not be the central point of our interest, bearing in mind the fact that WRS are predominantly dynamic, continuous, non-linear, multi-dimensional and stochastic systems.

In model design two different groups can be chosen:

a) methods of operation research,

b) cybernetic methods.

The difference between them lies in the complexity and probability character of the modelled system. Up until now, we have not been able to cross the borders between operation research methods and cybernetics, especially in practical applications.

Optimization of WRS functions, in theoretical studies and practical case studies, used, at best, methods of operation research with varying success and mathematical tractability. Some methods have failed even in dealing with relatively simple and not extended WRS with single (or a dominating) objective, as the model was not mathematically tractable.

Recently, some attempts have succeeded in using quite a new approach on a cybernetic basis. It can be stated that solution of some theoretical problems prepared prerequisites for the further development of these methods.

A promising optimizing method of operation research, suitable for less complex, but a stochastic systems, that can be described, e.g., statistically, is dynamic programming with some of its modifications, e.g., DDDP or incremental dynamic programming. All models of WRS using an optimization of this kind are, however, simpler than the actual WRS.

In principle, there are three possibilities of evolving a suitable method:

– simplification of the actual system in the model,

– decomposition of the system into several subsystems and their separate treatment,

– application of cybernetic methods.

In using the first two possibilities there is often a danger of oversimplification. The application of cybernetic methods seems to be effective if the system identified with the WRS is, in principle, cybernetic. The cybernetic adaptive control system can maintain its behaviour in the given acceptable limits and adapt to conditions that will occur in future.

13.2 CHARACTERISTIC PROPERTIES OF CYBERNETIC ADAPTIVE SYSTEMS

The processes in the operation of WRS have an adaptive character. Their properties are not Markovian, i.e., their state at a given moment does not depend on the states in a limited and constant number of previous time points, but on the whole history of the process. In the present methods of operation research applied in the reservoir systems operation and in the attempts of their use for dealing with the problems of WRS, the Markovian character of the process has mostly been assumed (stochastic methods of Markovian optimization). The most effective self-organizing adaptive control model is an ultrastable model, i.e., its organization tends to return, from each state and under all conditions, to the stable state. Its ultrastable feature is in contradiction to the Markovian character of the process.

The adaptivity of a system is given by maintaining the important variables within the required limits. The mechanism of this maintenance is automatic, and the system has an ability to adapt to any changes in its environment that might be the consequence of the impact of certain factors.

In principle, the variables and their feasible states, given within a certain range, must be determined in advance. In multi-purpose WRS these variables may include technological and economic values.

A precise definition of the boundary between the system and its environment, with stochastic impacts, is desirable.

The system is often decomposed into subsystems using the functional aspects, in fact, system behaviour aspects. We are primarily interested in information relationships, which may have an impact on the system variety reduction. Therefore, in the multi-purpose WRS, e.g., the geographical standpoint used for the identification of the system structure, must be regarded as less important.

The identified subsystems have to be connected by information relationships so that the output of one subsystem should be the input of a second one and vice-versa, developing in this way a feedback relationship. In such a manner the boundary subsystems and the system environment are interconnected.

The adaptive process takes place separately in the individual subsystems. Their states change as long as the stable state is reached when the principal variables are within the required limits. Each subsystem has its stability objectives, which can be mutually exclusive. The stabilization of one subsystem in a stable state can cause deviations of outputs of some other subsystems, which are influenced in their inputs. Therefore each subsystem can ignore the decision of any other subsystem, which would otherwise reach its stable state. It is necessary to solve this rather complex problem if an ultrastable system is to be reached, the system that searches automatically for ultrastability and tends, as a complex system, to a stable state for all stimuli that can enter on its input. The aim is an acceptable combination of given values (or ranges of values) of principal variables in the individual subsystems.

In Markovian processes, the current state depends only on the previous state or on several previous states and in controlled processes on the decision that was made immediately before the process transition to the current state, i.e.

$$S_k = S_k(S_{k-1}; S_{k-2}; \ldots, S_{k-s}; R_k) \tag{13.1}$$

where $S_k, S_{k-1}, \ldots, S_{k-s}$ are the states of the process in discrete times, R_k is the control that occured between defined instants or in a discrete instant k.

Unlike Markovian processes, in the adaptive process the state S_k depends on all possible information before the instant k, which is called historical information H_k.

The system, the behaviour of which is identified by this adaptive process, records in its "memory" all the couples of output responses and corresponding input impulses (i.e., all historical information). The effectiveness of these responses is evaluated, and the results of this evaluation are also recorded in its "memory". Such system "knows" which set of responses $\bar{R}$ corresponds best to the set of stimuli $\bar{P}$ as the set $\bar{R}$ has been evaluated as the most successful under given conditions of the process. This learning process of the adaptive control system is generally stochastic and non-Markovian. In modelling of WRS the transitive probabilities of moving the system to any feasible subsequent state can usually be determined beforehand in relation to the sequence of all previous stages, satisfying in this way the assumption of practical implementation of the model of such a system. The principle of development of the adaptive control model are, in general, very simple.

The way of learning in cybernetic adaptive systems with a non-Markovian character is a progressive form of learning as compared with the evolutionary process that generally occurs in nature and that is Markovian. The latter process is often denoted as a cumbersome learning process with relatively slow adaptation. An adaptive system identified with WRS has to control relatively fast changes and has to learn quickly from the historical information to identify and specify the purposeful behaviour, i.e., homeostatic ultrastability. It is not the process of survival typical for certain biological species. The evolutionary process is controlled only by the feedback loops (the successful mutations are strengthened by a positive feedback, unsuccessful ones are suppressed). The changes of environment which form the stimuli for the state change, often random, occur very slowly. Therefore this learning process is cumbersome and gradual.

Variety of the system is one characteristic of its complexity. The multi-purpose WRS are complex systems with a great variety of disturbing elements that affect them. In managing the system we try to control these disturbing effects and decrease their variety; decreasing variety is one possible way of system control.

In investigating the system functions we try to determine some relationships occurring in the set of disturbing effects, to attain the invariants of this set and in this way to reduce its actual variety; this can be achieved by adding further information.

The system, whose environment is thus investigated, cannot thus be simplified, but the conditions for better control are formed in this way as each step in the determination of relationships in the set of disturbing elements helps in forecasting the behaviour of the system.

It is necessary to distinguish the cybernetic adaptive systems and the pure stochastic systems (Aoki, 1971) with unique probability distribution functions of random parameters (or at least some statistical moments). Sometimes they are called systems with maximum incomplete, i.e., stochastic information. In the cybernetic adaptive systems a part of the basic stochastic information is missing and the probability distribution functions of some stochastic parameters depend on certain additional unknown random variables.

Modelling of WRS as a cybernetic adaptive control system will proceed along the following steps:

- definition of the cybernetic adaptive control system,
- description of the behaviour of the cybernetic adaptive control system,
- choice of the model with an adaptive character.

A definition of a system of this kind for WRS is not difficult in principle. It is only an unusual information standpoint in an investigation into relationships.

A detailed mathematical description of such system is not possible nor necessary in the investigation of its behaviour. In addition, if the cybernetic adaptive control system and its model are properly realized with ultrastability, they are able to give precision to their description during their functioning. A precise initial description is, therefore, not necessary.

The model is a mathematical and logical abstraction and its behaviour can be investigated so that it is realized:

- on a single-purpose facility, which is created for one task or for a group of tasks,

- on an analog computer (continuous modelling),
- on a digital computer (discrete modelling),
- on a hybrid computer system.

The application of the analog computers seems to be the most natural way for the first experiments with modelling of such cybernetic adaptive systems, although only certain problems with relative low accuracy can be dealt with in this manner.

In the preliminary stage their application is cheapest and computation is most effective. Digital computers seem to be the basic computer tool for the concrete tasks of modelling, while hybrid computer systems put the system into perspective.

The development of adaptive models of WRS can be performed in principle. Cybernetic adaptive models have been successfully developed in other technical branches.

13.3 CONCLUSION

Taking the basic assumption of dealing successfully with water resources problems, i.e., in the analysis of technological, economic and social impacts, much has been accomplished that facilitates the formulation of adequately simplified tasks and finding a form that is mathematically tractable under present conditions.

The development of new methodological approaches with corresponding means (technology) are so dynamic that there is a real hope for quick improvement in dealing with ever more complex task formulations, i.e., closer to reality. A mere extrapolation of the present achievements cannot meet our requirements. Futurological studies are hypotheses that certainly cannot be proved now. Without a doubt all over the world water management, water conservation, and the prevention of water resources pollution are the necessary prerequisites for the further development of mankind.

It is necessary to persuade the political and administrative decision-makers that water is irreplaceable in many functions and that there is a great danger arising from the limitation and pollution of water resources.

Not only in the minds of water resources engineers and planners, but public opinion also has to made aware of the idea of water as a renewable but exhaustible resource. Only in this way can the application of the results of scientific and technological progress in water resources management and engineering and in water resources systems be achieved.