MATHEMATICAL MODELS FOR WATER RESOURCES MANAGEMENT

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Summary

Growing human population faces the threat of severe stress due to water scarcity. Problems are accentuated by excessive use of limited water resources and deteriorating quality of available water. They are becoming increasingly complex and diverse and require more and more specific knowledge from both a technical and non-technical perspective. Due to the complexities there arises the need to understand the detailed technical aspects as well as broader managerial and social issues. These elements will increasingly demand an efficient integration of various disciplines, sectors, countries, and societies. The major challenges are whether we are capable of and prepared to realize the needed integration and whether we can bridge the existing large gaps and break the barriers. The paper analyzes major past and desired future trends in modeling of fresh water management. A number of issues are selected with regard to integrated water systems management, sustainable development and life support. The purpose of this paper is to give a short summary of some of the complex water issues that are faced by our modern world both at present and in the future, in order to serve as a background material for contingency planning of water research activities. The treatment is broad rather than in detail. Certain methodological basis was developed for regional decision-making and management to create opportunities for multi-factor and interrelated ecological and economic solutions as a part of rational planning. The river basin (watershed) approach is an effective methodological basis for elaborating such comprehensive solutions. Besides the water quality aspect, the watershed criteria for regionalization may as well be applied in taking into account other factors, both of ecological and social origins. The watershed concept has also a social dimension, which is especially important if we analyze the ecological processes by taking into account the external anthropogenic effects on life support systems.

1. Introduction

This section serves merely as a brief introduction to the subject. The themes prepared for this paper provide at least a partial review of modeling efforts. This introductory essay reviews a number of methodological grounds for water problems modeling.

The paper presents a review of a number of mathematical models for water resources and their quality management and an overview of the concepts and methods for assessing possible effects of climate change on hydrology and water resources. The key variables and parameters needed for evaluating projects of water resources management are identified and discussed. Improved management of water resources systems at all levels has recently received much attention. Ineffective legislation and institutional arrangements are one of the biggest barriers to efforts towards improvement and sound water management. The control and use of water to meet a great number of human needs has been and continues to be a fundamental element of socio-economic development and human progress. The earliest of civilizations have understood the uniqueness of water within the biosphere and the multiple, beneficial roles of water; as a sustainer of life, an enabler for development, and as a transporter of wastes. Regretfully, however, this exploitation of water does not always satisfy intense human demands and is often harmful to the environment through the deterioration of water quality and degradation of the surrounding aquatic ecosystem. From a global perspective, these issues were not of great concern until the twentieth century.

It is often accepted that water quality comprises all the properties of water besides its quantity, yet even quality can not be measured without reference to quantity. Contaminant concentrations are often expressed in terms of mass per unit volume, and only recently the mainstream water quality researchers have widely accepted the use of mass balances and mass flows in conjunction with concentrations.

The actual indices of water quality are never unambiguous; dominating parameters depend on uses, problems, space and time, and the subjective judgment of the analyst that cannot be excluded. Water quality may refer to physical, chemical, biological, and ecological characteristics of a water body. Water quality is also “body dependent”, as rivers, lakes and groundwater aquifers experience different quality problems. Water quality management is a commonly used and somewhat vague expression referring to the (systematic) usage of a set of non-technical measures and activities to maintain or improve quality according to the requirements of its uses and to “protect” its ecosystem. It is worthy to note that while the desired quality of a particular use can be expressed by “concentration”, ecosystem “goals” are harder to quantify leading to an additional subjective element of management.

Certain water quality criteria and standards are currently used by water-pollution-control authorities throughout the world, as well as by engineers and scientists. Water quality standards are either stream standards or effluent standards. The effluent standards determine how much pollution can be discharged from municipal and industrial wastewater sources and by some types of diffuse pollution. Performance standards, which are equivalent to effluent standards for the control of pollution from lands, are used to control pollution from subdivisions, construction sites, and mining. The stream standards can be related to the protection of aquatic habitats, which is one of the most important beneficial uses of water, and/or to other existing or intended uses of the water resource.

Growth of industrial, agricultural and municipal water consumption entails increased human impact on inland waters. Qualitative and quantitative changes in water resources can lead to considerable, sometimes irreversible modification of natural ecosystems and life support systems. That is why regional water economy planning should be based on system analysis of economic, social, hydrological, and ecological factors. This approach ensures an appreciable increase in the efficiency of scientific studies and improved decision-making, especially by the use of mathematical models.

Large water resources systems (WRSs) serve various industries as well as environmental protection. WRSs also serve water transport, hydrostations and other sectors of national economy and have become a very important ingredient of that.

The variability of river streamflow, the lack of co-ordination in time between demand and supply of water resources in natural conditions have led to the creation of water reservoirs. However, absolute regulation of river streamflow is not usually possible. It requires very large regulating capacities. Furthermore, the presence of reservoirs in the WRS requires the development of dispatcher rules governing their operation. In addition, many WRS are based on the water resources of natural and artificial reservoirs and they affect the environment more than other systems of the national economy. For this reason management of water resource systems becomes highly important. There is the water resources deficit practically in each WRS and certain probability of not satisfying the total water demand. This probability is one of the main characteristics of WRS defining the hydrological reliability of the functioning of the system.

Relations between water consuming and non water consuming productions form an inter-branch balance, determine the requirements of national economy to water resources and single out corresponding informational flows between them. Financial, material and labor resources are regarded as external constraints on water economy development. Therefore, the use of the models, simulating the development of national economy as a whole, can ensure the best theoretical proportions for developing inter-branch complexes.

Regional water economy planning is adequately described by a system of mathematical models that is formed from the models of individual subsystems. On the whole, methodological studies comprise the development of principles of modeling basic processes and principles of models combination into a dialogue system with a “man-computer” interface, as well as the justification of rules regulating the work of the dialogue systems, providing coordinated strategies and plans of water economy development.

Alongside the structure of targets and creating the tree of objectives, the system of investigation of water management tasks involves a correct statement of the problem. It means preliminary qualitative socio-economic and geographical analysis of the whole problem, estimation of possible influence of water management measures on the development of productive forces, social conditions, economy and environment, both on a global and regional scale. It also requires the exploitation of the achievements of fundamental and applied contiguous sciences in the domain.

For different types of water economy planning tasks the choice of the type of mathematical models is usually a compromise between the striving for detailed formalization and adequate description, on the one hand, and the necessity of efficient algorithm realization, on the other. Developments in information and computer technology, electronic communication, remote sensing, instrumentation, control, and modeling have already had a significant impact on comprising research, operation, planning, decision making, etc. Combining databases, models, and interfaces, i.e. the development of decision support systems (DSSs), offers opportunities for integration, analyses, and the consideration of complex water and environmental problems that were unthinkable before.

The general requirements for the system of mathematical models for water resources management boil down to: the need to harmonize the information and software; the chance to incorporate new problems arising from the changes in the plan prerequisites or the considerations of new aspects (approaches); possible substitution of mathematical models by more effective ones, oriented towards advanced software.

One should keep in mind that individual mathematical models in some system of models are generally autonomous enough. As a rule they are developed for certain purposes independent of each other and have limited fields of application. The system approach to water resources management allows justification of the choice of mathematical models and software ensuring maximum similarity in the description of processes and phenomena under consideration.

Statistical data, time series of observations of natural processes, quantitatively expressed development targets; projects, etc. are used as input data in tasks for water management. The equivalent of the collected information includes both the use of formalized procedures and informal analysis carried out by experts in individual branches. It is only natural that peculiarities of water resources management problems affect the mathematical models that were used for their solution.

The analyses can be performed using simulation, optimization, or both, depending on the management goal and the size and type of the problem. The critical issues in a mathematical model are the non-linearities, uncertainties, multiple pollutant nature of waste discharges, multiple objectives, and spatial and temporal distribution of management actions.

Mathematical models for selection are revealed in a process of water problems analysis. The multifaceted nature of the tasks for large river basins to be solved and vast areas of river basins involved necessitate the decomposition of the general problem of the whole basin both over disciplinary directions (individual problems) and over territorial units. The main types of division into areas are administrative and hydrographic ones. Within each problem, decomposition is carried out over the size of the analyzed water bodies in different systems of territory division. For example, within the framework of hydrographic ones, the whole river, its main parts, water management zones, tributaries and local zones can be distinguished. For each size unit, an independent group of tasks is set within the general problem. In the system of tasks so formed, each type of division into areas task for objects of certain size is realized as a set of mathematical models with information links between all the tasks.

The structure and the type of the used mathematical models are determine by the following special features of water resource system (WRS):

- WRS are structurally complex as the result of the heterogeneity of interacting elements: stream-flows, reservoirs, canals, hydropower stations, industrial enterprises, irrigated lands, etc.
- Water resources are used in the interests of different branches with ensuing conflicts between the related parties.
- The system is dynamic in the course of years bringing about respective changes in its structure and parameters; besides, it is characterized by seasonal fluctuations in water supply and withdrawal values. Therefore, we need special regulations of its management and we should study the reliability of the decisions making.
- It is necessary to evaluate the anticipated effects of climatic and anthropogenic impacts on the environment and, in particular, on aquatic ecosystems and to elaborate policies precluding possible adverse effects of the WRS functioning, such as the pollution and eutrophication of water bodies, soil salinization and degradation, the shallowness of rivers, etc.

The next sections address mathematical models for two purposes: a) water resources planning; b) water quality management.

2. Mathematical modeling in water resources planning

2.1. Total state

Every stage of water management planning determines the required suitable degree of detail of input data and final results. This generates a need for using system of optimization and simulation models and their combinations. They usually comprise three basic components:

- A system of interrelated models used to determine quantitative and qualitative characteristics, relevant to a certain river basin. It is methodologically important to find in this system a proper place for rather "coarse" large-scale models and detailed local ones used to optimize water resource use and protection, and the simulation models: in accordance with their role in the river runoff and water quality formation, in forecasting future industrial, agricultural and municipal water consumption;
- Software of the dialogue "man-computer" systems, ensuring the participation of decision-makers in model calculations, appropriate data processing and representation of the results obtained with the use of the computer;
- An approach ensuring efficient application of the above mentioned systems to the decision-making process.

Singling out autonomous subsystems in water economy ensures more detailed investigation of the latter. The planning process is reduced to an interactive procedure of co-ordination the development strategies and operation of the subsystems. The concept of hierarchic systems of interrelated models for water economy development corresponds to the above mentioned approach. In this case, principal relations between the elements of the system are analyzed. It prevails over the study of elements themselves and their internal regularities. These regularities are studied using models of lower hierarchic level.

According to the scale of description, models may be divided into large-scale models, local models, and models used for input data processing. The large-scale models describe the most important relations and variants of the general development of the system. They allow revealing basic water management problems and determining the way of their solution. The large-scale models make it possible to identify the zones for rational solution options that serve to form the alternatives for continuous research. The local models make it possible to carry out a thorough analysis and economic evaluation of the alternatives selected at the stage of computation by the large-scale models.

The hierarchical structure of water resource systems, as such, dictates the structure of the model. For better adequacy the development of a system of models should begin with the models of the simplest processes of forming and use of water resources, i.e. models of plants growth, water consumption processes in different industries, and flow formation on watersheds. Such an approach could provide for better accuracy of the models, however the structure of the resulting system would be highly sophisticated. In addition, incomplete knowledge of many processes will bring considerable errors into corresponding models. So the resulting system of models may turn out to be completely useless for practice.

Thus, it is highly important to substantiate the depth of detail description in modeling the management system of WRS. Such substantiation should be based upon the required accuracy of the model with respect to the specific purposes of the analysis. The models of flow formation and plant growth, for example, give a forecast of corresponding processes in natural conditions. In principle, they may be used as a base for models of the WRS management. However, the transition from the description of local processes to characteristics of the regional level or a typical water consumer is not at all trivial. Special research is needed reveal the influence of natural parameters, which may be called the "background" parameters. But the introduction of background parameters makes the local models rather "shallow".

Thus it seems quite reasonable to use a priori rough description of natural processes in management models. It applies to the connection of natural factors with the yield to the water mass balance, to transfer and transformations of admixtures etc. The minimal "cell" of modeling is usually a typical water consumer was characterized (in particular, with the use of models) by the functions of efficiency of the use of water resources. The most acceptable territorial unit in modeling the water economy is the river basin because of the closeness of water resources and uniqueness of the source of water supply which relates the water users located inside the state of the ecosystem. Planning on the river basin level allows composition of a complex multi-sectored development program balanced with respect to the main natural resources.

The system of interacting water management models makes it possible to reflect adequately some features such as incompleteness of information on facilities and systems, current and future targets and demands on various indices, as well as on their reliability, which in principle cannot be eliminated. These difficulties, inherent in the WRS, are generally characteristic of tasks of managing economic systems. Nearly all economic parameters (cost, efficiency rate, etc.), just like engineering and other indices, are actually approximate values. Under modeling the assessment of these indices will become more accurate. Besides, the use of formalized procedures determines the validity of management decisions, being made both today and in the foreseeable future.

The nextt section deals with classes of mathematical models describing different stages of water resources planning and management.

2.2. Classes of models of water resources planning and management

The structure and type of mathematical models for the solution of water problems are determined by their engineering importance. Completely distinguished tasks of water resources planning and management have 3 stages:

- evaluation of alternatives and scenarios of water economy and WRS development in the region;
- determination of the WRS parameters;
- study of the water resource systems operation regime.

The first stage of planning is usually a long-term one. It envisages elaboration of economic, social and engineering alternatives and corresponding scenarios of national economy development. This stage also assumes multi-alternative estimation of the allocation of water-consuming enterprises, ensuring harmony between planning regional economy by introducing plan targets for industrial production output and restrictions on additional resources.

The second stage envisages techno-economic estimations to substantiate the WRS parameters within the limits of the hypothesis of water economy development, adopted at the first stage. The problems are solved using various optimization and simulation models. A graph model interpretation of the WRS (linear flow scheme) is traditionally used in planning and project calculations at this stage, determining the conditions and quality of its functioning. The model allows us to solve the problem of the WRS management with different degree of the account of natural factors variability and fix the structure and parameters of the system and the regime of water use by control complex participants.
At the third stage the long-term dynamics and parameters of the system operation are studied in detail. If they do not meet the requirements of water supply reliability, or the depth of water deficit, or any other standard, it is regarded as a signal to reconsider some of parameters and even certain hypotheses of water economy development in the region. The final scheme of the WRS development is adopted by decision-makers, taking into account the results of the solution of the above problems and non-model analysis.

The studies of all stages of water resources management include the development of two classes of mathematical models: optimization and simulation. Optimization models, which are used for: a) optimization of land and water resources use. They are designed for the estimation of agricultural production ability. Land irrigation water projects' development is considered in particular. The model input data (crop yields and irrigation rates) are performed on an annual basis. The model has two or more groups of objective functions of economic or principal type, including the minimization of total costs, maximization of production benefits for every region or every farm, or maximization of output of a given commodity, etc; b) determination of the WRS parameters according to one or more optimality criteria. The parameters include the composition and capacities of planned reservoirs, areas of irrigated lands, installed capacities of hydro power plants, navigation indices and so on. Amount of water resources with given provision level available from surface sources and usable storage of ground water are given exogenously as well as water demands of some users not included into the models. Optimization models perform a screening function by identifying “optimal” management alternatives.

The second class of models consists of simulation models oriented to validation of the obtained parameters and to the determination of the system control rules in the future operation conditions. Both the stages are necessary for making a reliable decision concerning the development of a multi-purpose WRS. To guarantee adequacy the optimization process is subdivided into two stages. Different criteria are used as objective functions.

The upper-level (large scale) optimization models permit solution of general problems in planning the development of water economy by taking into account the forecasts of the volumes of the required industrial output and in accordance with the available resources of water, land, labor, etc. Such models will be discussed later on.

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Biographical sketch

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