Teaching the systems approach to water resources development

A contribution to the International Hydrological Programme

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A contribution to the International Hydrological Programme

Teaching the systems approach to water resources development

A state-of-the-art report by IHP rapporteur
L. J. Mostertman

Unesco
Although the total amount of water on earth is generally assumed to have remained virtually constant, the rapid growth of population, together with the extension of irrigated agriculture and industrial development, are stressing the quantity and quality aspects of the natural system. Because of the increasing problems, man has begun to realize that he can no longer follow a "use and discard" philosophy—either with water resources or any other natural resource. As a result, the need for a consistent policy of rational management of water resources has become evident.

Rational water management, however, should be founded upon a thorough understanding of water availability and movement. Thus, as a contribution to the solution of the world's water problems, Unesco, in 1965, began the first world-wide programme of studies of the hydrological cycle—the International Hydrological Decade (IHD). The research programme was complemented by a major effort in the field of hydrological education and training. The activities undertaken during the Decade proved to be of great interest and value to Member States. By the end of that period, a majority of Unesco's Member States had formed IHD National Committees to carry out relevant national activities and to participate in regional and international co-operation within the IHD programme. The knowledge of the world's water resources had substantially improved. Hydrology became widely recognized as an independent professional option and facilities for the training of hydrologists had been developed.

Conscious of the need to expand upon the efforts initiated during the International Hydrological Decade and, following the recommendations of Member States, Unesco, in 1975, launched a new long-term intergovernmental programme, the International Hydrological Programme (IHP), to follow the Decade.

Although the IHP is basically a scientific and educational programme, Unesco has been aware from the beginning of a need to direct its activities toward the practical solutions of the world's very real water resources problems. Accordingly, and in line with the recommendations of the 1977 United Nations Water Conference, the objectives of the International Hydrological Programme have been gradually expanded in order to cover not only hydrological processes considered in interrelationship with the environment and human activities, but also the scientific aspects of multi-purpose utilization and conservation of water resources to meet the needs of economic and social development. Thus, while maintaining IHP's scientific concept, the objectives have shifted perceptibly towards a multidisciplinary approach to the assessment, planning, and rational management of water resources.

As part of Unesco's contribution to the objectives of the IHP, two publication series are issued: "Studies and Reports in Hydrology" and "Technical Papers in Hydrology". In addition to these publications, and in order to expedite exchange of information in the areas in which it is most needed, works of a preliminary nature are issued in the form of Technical Documents.

The "Technical Papers in hydrology" series, to which this volume belongs, is intended to provide a means for the exchange of information on hydrological techniques and for the coordination of research and data collection. Unesco uses this series as a means of bringing together and making known the experience accumulated by hydrologists throughout the world.
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The educational programme of the International Hydrological Programme is a follow-up of the activities carried out by the International Hydrological Decade (1965-1974) but the scope has been broadened to include the various applications of hydrology to the development and management of water resources. It also envisages the extension of hydrological education in two directions: firstly, the continuation of the training of highly qualified hydrologists and secondly, the training of specialists and technicians. At the same time it is essential to integrate teaching with scientific research and with professional practice.

The Intergovernmental Council for the IHP established a programme of publication in the field of hydrological and water resources education, partially to replace older IHD publications issued around 1972 or to treat fields which so far had not yet been covered. The Council established a working group on Teaching Aids which met in Padova, Italy (March 1976), Paris (October 1979) and Paris (September 1981) with the main aim of preparing four publications to be issued by Unesco.

(a) Teaching the systems approach to water resources development
(b) Teaching the use of computers in water resources development
(c) Experimental facilities in water resources education
(d) Teaching aids in hydrology

The Council entrusted Professor L.J. Mostertman (Delft, The Netherlands) with the task of compiling the present publication.

This publication is intended to serve both teachers and students of water resources systems in order to enable this field to be included successfully in post-graduate study programmes. The other publications mentioned above are complementary and the reader of this publication is advised to study also the paper on the application of computers in water resources development.
The systems approach to water resources development

1.1 Definition and characteristics

Water-resources development projects are very complex because of the multitude of factors influencing their performance and because of uncertainty related to them. An analysis of such projects should take into account the many interactions between these various factors. Systems analysis is a methodology for investigating these relations, so that the consequences of decisions with regard to water-resources schemes and kinds of water use can be evaluated.

The systems analysis approach in water-resources development is often used as an instrument in the planning and design process. The approach will, however, also yield good results in the programming of the maintenance and of the management of the engineering works.

The issues involved in water-resources development belong to the public sector. The identification of the objectives of such works involves political aspects. They can only be defined after many deliberations. An optimal solution obtained by the analysis may not be feasible because of political constraints. Fortunately an optimal solution is often only a little better than the non-optimal solution that will ultimately be implemented as it is politically feasible.

The general characteristics of the systems analysis of an activity are:
- Clear objectives are set for the activity.
- There is a data base of known variables from the hydrological or social sciences.
- The values connected with each outcome of the activity can be calculated or estimated.
- There are various courses of action that can be followed.
- The cost connected with various courses of action can be determined.
- There exist a certain number of constraints which limit the choice of feasible solutions.

1.2 Short history

From the beginning of the 20th century a more systematic approach to water-resources planning was introduced. The statistical nature of hydrological variables and of predictions of water use was recognized. At a later stage economic variables were combined with these statistics in order to maximize benefits. The systematic analysis of cost and benefits of water development schemes dates from the years thirty of this century.

The need for a rational method for the solution of logistic problems led in the years 1940-1945 to the development of a methodology, that became later known as operational research. In the beginning years it was mainly applied in industrial management. The proceedings of the first International Conference on Operational Research held in 1957, contain only one paper related to water-resources development. In the following years the techniques of operational research became more frequently used by water-resources planners. The size of water-resources systems and the need to involve several conflicting viewpoints gradually led to a more comprehensive approach in which the water-resources scheme with its impacts was studied as a coherent system. The various operational research techniques were adapted to be applied in this approach.

Because of the vast amount of variables involved in water-resources projects, calculations were cumbersome or not feasible. The advent of the electronic computer that helped managing large sets of data made further developments possible. For the application of the computer to decision problems in various fields the expression "systems analysis" came in use. Nowadays the term "operational research" is no more currently used for water-resources studies but it has been replaced by the term "systems analysis".
2 Manpower needs

2.1 Work in a team

The analysis of a major water-resources system will have to be undertaken by a multidisciplinary team. Engineers, hydrologists, economists and social and political scientists may be members. They should be familiar with the philosophy of systems analysis and they should have an appreciation of the contribution apportioned by the various disciplines involved and the techniques applied. For normal practical cases a water-resources engineer will conduct the team in charge of the analysis of the system. This team need not always include a professional systems analyst. His task is the development of new techniques. He will also be consulted if proposed systems tend to become over-complicated. The professional analyst can help to avoid that the model becomes so complicated that it exceeds the ability to estimate parameters. One should be very well aware that complexity is not a measure of technical competence, but simplicity is. For most assignments the case to be analysed will be similar to one that has already been analysed elsewhere. The latter can then be used as a model so that there is no need to develop a new method. It remains, however, prudent to have any completed analysis checked by a professional systems scientist.

2.2 Staff from various disciplines

For the analysis a sound data base is required. Dependent on the nature of the assignment such data come from hydrology, climate and weather, topography, geology, soil science, distribution of population. The personnel charged with data collection should have an appreciation of the requirements set by the systems approach. This is especially true for the network of hydrological observations. Where continuous recording is not possible, observations have to be made at specific time intervals. The length of these intervals will affect the quality of the parameter estimation. The hydrologist should be well aware of this.

Often the analysis implies a choice among various technical solutions. Designs of the main dimensions of works and an estimation of their cost will have to be prepared then in advance. Working out the alternatives in great detail will be too costly. The water-resources design engineer should therefore know how to make such preliminary designs, including cost estimates without excessive design cost and within a limited period of time.

The economist has a key role. He will help in determining the objective functions. By study and experience he should be familiar with mathematical economics and model building. Even the best systems analysis would lead to unacceptable decisions if the sociological aspects are not taken into account and if the users concerned are not involved in the decision process. A sociologist or a social anthropologist will therefore either have to be a member of the team or have to be consulted by it.

The water-resources planner will have to present the results of his analysis in such a shape that the political decision makers will have several alternatives before them, each with their economic and social consequences. Where this material will be presented to public or private pressure groups the water-resources specialist needs skills in communication with such groups.

It is only by the extraordinary capacity of the modern computer that vast systems can be analyzed. Therefore the services of an electronic computer and a programming staff should be available.

One will have to consider well whether it is possible to teach to the same person, in addition to the wide range of techniques now available for systems analysis, also the always
widening variety of hydrological subjects and of hydraulic engineering techniques. In answering this question one should consider, however, that the intellectual exercise of following the systems approach will enhance the capability of dealing in an efficient way with a variety of other tasks.

2.3 Needs for training

In the context of the International Hydrological Programme the training of the following types of personnel for systems analysis is recommended:

1. A number of specialists in systems sciences and in computer applications will have to be initiated in the special requirements for the application of their discipline to water-resources development. This can be done by in-service training or by short-term seminars.

2. Water-resources engineers or hydrologists who have to take a leading role in the systems analysis team need a wide grasp of relevant techniques and procedures. They can be trained in post-graduate programmes with water-resources systems analysis as major subject.

3. All professional hydrologists and water-resources engineers should study the systems approach, its potential and limits of application. In order to reach this objective systems analysis should be taught as a course subject in all programmes for training hydrologists and water-resources engineers.

4. Water-resources engineers and most hydrologists are recruited from the civil engineering profession. They should study as early as possible the basic subjects required for systems analysis and be initiated in the subject itself. The consequences this has for their under-graduate study programme will be discussed in par. 3.2.

5. Managers and political decision makers dealing with water-resources systems should get an appreciation of what the systems approach may offer for the improvement of the quality of their decisions. This aim can be reached by short-term seminars or by compiling publications directed at their needs.
3 Systems analysis in curricula for hydrologists and engineers

3.1 Introduction

As we are concerned in this publication mainly with the education of hydrologists and hydraulic engineers, this discussion will be limited to the place of systems analysis in curricula for this type of personnel. Professional hydrologists are rarely trained at undergraduate level, their undergraduate education is mostly in civil or a related branch of engineering. Therefore undergraduate programmes for civil engineers will be considered in par. 3.2. The role of systems analysis in post-graduate programmes for hydraulic engineers and hydrologists will be discussed in par. 3.3.

3.2 Undergraduate programmes for civil engineers

One can hardly expect that it will be possible to teach the full range of subjects related to systems analysis within an undergraduate course for civil or hydraulic engineers. It is necessary to devote much time to fluid and soil mechanics, structural analysis and other engineering subjects. During undergraduate education, however, the ground can, and should, be prepared for later studies in systems science by offering a number of relevant auxiliary subjects. Fortunately most of these subjects are also needed for the use of mathematical models in other civil engineering applications. Such studies will make it much easier to master, during later post-graduate instruction, the methods of systems analysis.

Each student will in the first line learn how to converse with the computer. In his mathematics course he will be taught some numerical methods, that enable him to translate mathematical expressions into a language readable by the computer. It is furthermore recommended that the mathematics course contains matrix algebra and differential equations, including Lagrange analysis.

Fortunately these subjects have already been widely introduced into most civil engineering curricula. Where this is not the case, the programmes should be adapted because the need for these subjects is nowadays also felt in several other branches of civil engineering. It will further be possible to start, already at undergraduate level, with the teaching of a number of techniques of operational research, specifically linear programming, optimization techniques and simple queueing theory.

It is of utmost importance that the engineering student acquires as early as possible in his studies, some familiarity with subjects from the social and economic sciences. A good course in engineering economy, including financial project analysis and an introduction to the estimation of social cost and benefits, can be considered to be a minimum requirement. If possible a course in political sciences, including the organization of government at various levels and the processes of political decision making, should be offered.

It is desirable that lectures on these subjects be illustrated by examples from water-resources development and that students solve some practical problems.

3.3 Post-graduate programmes

Lack of time may be an obstacle to the inclusion of systems analysis into a course for hydrologists or for hydraulic engineers. The teaching of modern surface and groundwater hydrology requires at least a full academic year. Teaching within the same course systems analysis will be at the sacrifice of hydrological subjects. Limitation of the detailed treatment of hydrology
to either surface water or ground water would clear the time needed. Similar conditions will 
prevail for a post-graduate curricula for hydraulic engineers. Study of the hydrological 
principles together with the design and execution of hydraulic structures in rock, concrete 
and steel will leave not much time for systems analysis. It will hence be preferable to offer 
two different types of courses for hydraulic engineering. The first of them concentrates on 
the design and execution of hydraulic engineering structures. The second one deals more deeply 
with the planning of the water resources development scheme together with a study of the 
systems approach.

As has been mentioned in par 2.3, there will also be a need for a post-graduate course 
mainly dealing with systems analysis and in which hydrology and engineering aspects are 
auxiliary subjects.

The systems approach finds a growing field of application in water quality engineering. 
The process design of treatment works should be based on an optimization between the cost of 
treatment and the retributions to be paid for the discharge of remaining pollutants. As the 
operational research techniques applied here are relatively simple and could be standardized, 
it will be feasible to introduce systems analysis, also in post-graduate curricula for sanitary 
or water-quality engineers.
4 Teaching of auxiliary subjects

Theory and application of systems analysis in water-resources development requires a background in a few subjects from the social sciences as well as a mathematical culture. The following review cites a number of subjects which are important, if not essential for systems analysis of water resources, and that are often not included in undergraduate curricula for civil engineers.

4.1 Subjects from the social sciences

4.1.1 Political science

The students should have an overview of the way in which political decisions are taken on various levels of government. They should acquire an insight into the distribution of responsibilities among various sectors and the different levels of government and into the flow of information in vertical and horizontal directions. It is of special importance that the engineer has a right appreciation of the limitations of his own task and responsibilities, so that he will not be tempted to influence the political decision mechanism in an undue way. It will not be possible to make a general statement on the number of hours to be spent on this subject. Much will depend on the previous exposure of the students to politics and political sciences.

4.1.2 Economics

The future analysts should have an overview of general economics with a certain bias to micro-economics. General subjects as demand and supply relations, the distribution of labour, employment, theory of financing of projects have to be included. Special attention should be paid to the economics of the various objective fields of water development, like floodcontrol, irrigation and drainage, power generation, watertransport and recreation.

4.1.3 Engineering economy

An analysis of social cost and benefits of water resources development projects, is one of the most important prerequisites for systems analysis. The analyst should have a good insight into ways of quantifying cost and benefits, including cases where market prices do not reflect social priorities or where no market exists. Various philosophies of discounting will have to be assimilated together with decision criteria, as the ratio between benefits and cost and the rate of discounted cash-flow. Experience shows that students from various cultural backgrounds often find great difficulties in grasping this theory and in some cases they even find it difficult to accept the underlying philosophy. Engineering economy should therefore be taught at not too rapid a speed and many exercises should be compiled. The teacher should be aware of the students' cultural background.

4.1.4 Project financing

Each water resources development project should fit into the overall budget of the government or other financing organization that has to finance it. The planner should therefore have an overview of the ways of financing a project, also during the period of operation. He should have an overview of various sources of capital for project financing, like rates and taxes,
gifts, loans and credits. He should be able to draft, for a project a cash flow study, including the time perspective of future money flows. Water resources planners working in developing countries should know the way of operation of international organizations for technical assistance and project financing.

4.2 **Mathematics and statistics**

4.2.1 **Mathematics**

Familiarity with a number of mathematical techniques is necessary for the analysis of a water-resources system. The mathematics curriculum of each specific course will depend very much on the students' previous education. In most cases there will be a need for matrix algebra, ordinary and simple partial differential equations, Lagrange multipliers. The systems analyst should be able to transform differential expressions into finite difference form so that they can be solved with the aid of the computer.

4.2.2 **Computer programming**

Systems analysis could only be developed due to the availability of the electronic computer. Hence it is the most important tool used. The student should become well versed in working with different types of computers, not only for calculations but also for the storage and retrieval of data.

4.2.3 **Statistics**

Statistics is essential for most water resources studies, because of the stochastic nature of hydrological processes, and of patterns of water use. Many students find it difficult to acquire an appreciation of the subject and to understand statistical reasonings. Statistics should be taught at a leisurely pace and there should be sufficient time for working out problems. Demonstrations and the use of simple experimental games may help in understanding.

The main role of statistics is to help estimate parameters. Therefore it is not enough to teach conventional subjects like summarizing data, distributions and correlation and regression. Statistical inference, Bayesian estimation and related theory should be included.

For several applications, as for instance the operation of reservoirs, a study of the theory of stochastic processes will be required.
5 Practical exercises

5.1 Problem work

The various operational research techniques and the methods for the statistical estimation of parameters can only be mastered by working-out problems. These problems should as far as possible be related to practical situations. Non-essential features of each technique can easily be grasped. In order to deal with as many different techniques as possible within the available hours, the individual assignment should not be too time-consuming. A computer should be used where applicable. Students can then also get a knowledge of the available sub-routines.

5.2 Case studies

For transferring the skill of conducting the systems analysis of a practical case it is essential to assign a major system for the students to follow from data base to final design. Where the case is based on a vast amount of data, much time will be required for their handling. Sets of data taken directly from the field often lack coherence, which will further add to the work load. It is, therefore recommended that such sets of field data be adapted by the teaching staff so that without sacrificing completeness and depth of treatment their amount is reduced. The student will then receive his assignment in the form of a file with all necessary maps, graphs and tables. This compilation will make a heavy call upon the inventiveness and work capacity of the teacher. Training institutions should have a collection of hydrological and meteorological yearbooks, as well as a sufficient variety of clear topographical, geological and soil maps, so that they have material to compile case studies and exercises.

It is important for the water resources designer or operator to know when systems analysis should not be used. Therefore it will be most helpful to follow also through a case where systems analysis failed to yield significant results. In this way it can be prevented that analysts are bred who consider the method to be infallible.

5.3 Integration with design work

A training programme for water-resources engineering will normally imply the working out of a comprehensive design. It is recommended to follow immediately the systems approach in such design work. This helps the students to grasp the practical value of systems analysis. They also acquire experience of the way in which the various phases of the design follow each other in logical sequence. In addition, this contributes to the efficiency of the design work as the same data can be used throughout all stages of the study. The analysis of the complete system can then be undertaken by a group of students. In the following design stage each student can then carry out the more detailed design of one of the components. Alternatively various students can each be assigned to work out a different solution. At the end of the assignment students can compare their individual results and see how these fit into an overall picture. Wherever time is available, they should conclude their design work by a study of the operation and maintenance of the system.

5.4 Co-operation among various disciplines

Ideally a study assignment in systems analysis should be worked out by a group of students representing various professional backgrounds. This requires the co-operation among faculties
of a university, or a common activity of an institute of technology and a school of economics. In practice it will often be difficult to organize such groups, not only because of conflicts of scheduling but also on account of the differences in professional idioms. Some extra time must, therefore, be available. The high pedagogical value of such an exercise makes it, however, worthwhile to spend this additional time. The analysis should not be considered terminated with the end of the computations. The results should be discussed in the group; if possible various policy viewpoint should be represented, so that the discussions simulate the decision mechanism in real life.

5.5 Management games

Where the water-resources development scheme can be realized in successive stages or where operational problems are involved, a management game is an excellent tool of instruction. The students are to form small groups of five to eight persons. Each group acts as a planning or managing board; it should, wherever possible, be multidisciplinary and each individual in the group will be asked to represent an interest. The group meets during a few successive days, each day or each half day of groupwork representing one year in reality. Each group will have to decide independently on the planning or operation of the system. A few teachers acting as umpires can critically follow the work of the various groups and they can be consulted when difficulties arise. At the end of a period of work representing a few years the results obtained by the groups are compared and evaluated. The management game is not only a learning aid for systems science, but it also helps studying group decision making. An explanation by a professional sociologist or psychologist, who has been following the proceedings of the game, will give the students an insight into the various interactions within their group and will help them to become more effective in teamwork.