PART I

Overview

This book on water resource systems planning and analysis is concerned with the development and application of quantitative mathematical modeling methods to problems of water management. Quantitative modeling methods are typically discussed in books or courses on operations research or systems analysis. In contrast to such texts on systems methodology, the primary focus of this book is on the application of these methods to problems of water management. The introductory chapter that follows provides a perspective on the types of water problems that are most readily analyzed using systems methods and explains why such quantitative methods can be, and have been, helpful during the planning process.

CHAPTER 1

Planning and Analysis of Water Resource Systems

1.1 INTRODUCTION TO WATER RESOURCES PLANNING

Water: too much, too little, too dirty. Throughout the world, these are the conditions that prompt water resources planning. To meet the demands for the desired quantity and quality of water at particular locations and times, engineers—together with economists, political scientists, lawyers, planners and conservationists—have gained considerable experience in designing, constructing, removing, and operating structures and implementing nonstructural measures that will permit improved management of natural water supplies.

The incentive to plan for increased control of any water resource often follows a major disaster, such as a flood, a drought, intolerable water quality conditions, or a waterborne disease epidemic. Following the crises that often trigger water resources planning, citizens' review committees, planning boards, advisory groups, and public hearings may all help sustain the momentum needed to carry plans through to implementation. Just as rapidly as public support develops for investments in engineering structures for controlling and managing water, environmental and preservation interest groups emerge to critically question the wisdom of such investments. The concern of these groups is not limited to just the conservation and preservation of scenic areas and wild rivers, but often includes the broad regional impacts that could result from changes in air and water quality, noise levels, land use, and transportation corridors. Even if the issue is the improvement of water quality, generally considered a desirable goal, the opposition will certainly include some of those who must pay to achieve it. The issues that create conflict in water resources planning are real and are not necessarily the result of human stubbornness, self-interest, or inflexibility. Reasonable, rational, and informed individuals will frequently reach opposing conclusions concerning the wisdom of proposed projects because of the differences in their assessment of the value of the costs and benefits of the projects.

Water resources planning must take into account multiple users, multiple purposes, and multiple objectives. Different people have different goals, perspectives, and values. Planning for maximum net economic benefits "to whomsoever they accrue" is not sufficient: it matters *who* pays and *who* benefits. Issues of equity, risk, redistribution of national wealth, environmental quality, and social welfare are as important as economic efficiency. It is clearly impossible to develop a single objective that satisfies all interests, all adversaries, and all political and social viewpoints.

Increased public involvement in water resources planning has changed the manner in which engineers approach this task. It has forced tradition-bound planners and designers to broaden their perspective and to examine a wider range of alternative plans. It has shifted more of the responsibility for making choices from the engineers or planners to the politicians or public officials. Even though engineers and planners play an important part in the decision-making process, it is elected politicians who are, or at least should be, responsible and accountable for decisions that involve compromises among various public interests and concerns.

Water resources engineers and planners should develop a number of reasonable alternatives for public officials to consider; they should also evaluate the economic, environmental, political, and social impacts that might result from each alternative. Today we study river basins, lakes, estuaries, and other water resource systems with a greater awareness of their complexity, their sensitivity and adaptability to exogenous forces, and of our own limitations in understanding their behavior. We realize the general irreversibility of the impact of large projects on natural ecosystems and on our own social and economic organization. Construction of large reservoirs commits valuable land and water resources to a limited range of uses and thus forecloses society's options to use these resources in very different ways. This awareness is humbling, but it is also a challenge. It has stimulated the development, over the last several decades, of improved analytical tools and methodologies for defining and evaluating alternatives for managing such systems so that the best possible decisions will be made.

Those who are involved in the development of water resource systems methodology know that the use of these tools cannot guarantee development of optimal plans for water resources development and management. Given the competing and changing objectives and priorities of different interest groups, it is unclear how useful the concept of an "optimal plan" really is. What system methodology can do, however, is to help define and evaluate, in a rather detailed manner, numerous alternatives that represent various possible compromises among conflicting groups, values, and management objectives. In particular, a rigorous and objective analysis should help to identify the possible trade-offs between quantifiable objectives so that further debate and analysis can be more informed. The art of systems analysis is to identify those issues and concerns which are important and significant and to structure the analysis to shed light on these issues.

Although the systems approach to water resources planning is not restricted to mathematical modeling, models do exemplify the approach. They can represent in a fairly structured and ordered manner the important interdependencies and interactions among the various control structures and users of a water resource system. Models permit an evaluation of the economic and physical consequences of alternative engineering structures, of various operating and allocating policies, and of different assumptions regarding future flows, technology, costs, and social and legal requirements. Although this systems methodology cannot define the best objectives or assumptions, it can identify good decisions, given those objectives and assumptions.

In acknowledging the role of systems methodology in the water resource planning process, one should recognize the inherent limitation of models as representations of any real problem. The input data, including objectives and other assumptions, may be controversial or uncertain. Of course, these inputs affect the output. Future events are not known with certainty, and our knowledge concerning any water resource system is always limited. Moreover, the results of any quantitative analysis of alternatives are often only a small part of the input to the overall planning and decision-making process. Equally important may be purely qualitative factors, including subjective inferences drawn from the quantitative analysis.

We should not expect, therefore, to have the precise results of any quantitative systems study accepted and implemented. A measure of the success of any systems study resides in the answer to the following questions: Did the study have a beneficial impact in the planning and decision-making process? Did the results of such studies make the debate over the proper choice of alternatives more informed? Did it introduce competitive alternatives which otherwise could not have been considered?

There seems to be no end of challenging water resource systems planning problems facing water resources planners. How one models any specific water resource problem depends on (1) the objectives of the analysis; (2) the data required to evaluate the projects; (3) the time, data, money, and computational facilities available for the analysis; and (4) the modelers' knowledge and skill. Model development is an art, requiring judgment in abstracting from the real world the components that are important to the decision to be made and that can be illuminated by quantitative methods, and judgment in expressing those components and their interrelationships mathematically in the form of a model.

1.2 WATER RESOURCE SYSTEMS ANALYSTS, ENGINEERS, AND POLICYMAKERS

To engage in a successful water resource systems study, the systems analyst must possess not only the requisite mathematical and systems methodology skills, but also an understanding of the environmental engineering, economic, political, cultural, and social aspects of water resources planning problems. For example, to study the impact of a large land development plan, the analyst should be able to predict how the proposed plan would affect runoff and, in turn, the quantity and quality of surface waters and groundwaters, and how the development would affect flood flows and conversely, how flood flows would affect the planned development. The analyst must have an understanding also of the biological, chemical, and physical processes that are influenced or caused by various nutrients, biodegradable wastes, chemicals, and other constituents that may be discharged into and transported by water bodies as a result of the proposed development.

A reasonable knowledge of economic theory is just as important as an understanding of hydraulic, hydrologic, and environmental engineering disciplines. Economics has always had, and will continue to have, a significant role in the planning of water resources investments. It is obvious that the results of most water resources management decisions have a direct impact on people and their relationships. Hence inputs from those having a knowledge of law, regional planning, and political science are also needed during the comprehensive planning of water resource systems, especially during the development and evaluation of the results of various planning models.

Early water resource systems studies were often undertaken with a naive view of the appropriate role and impact of models and modelers in the policymaking process. The policymaker could foresee the need to make a decision. He or she would tell the systems group to study the problem. They would then model it, identifying feasible solutions and their consequences, and recommend one or at most a few solutions. The policymaker, after waiting patiently for these recommendations, would then make a yes or no decision. Experience to date suggests the following:

1. A final solution to a water resources planning problem rarely exists; plans and projects are dynamic and change and evolve over time as facilities are added and modified and the uses and demands placed on the facilities change.
2. For every major decision there are many minor decisions, made by different agencies or management organizations responsible for different aspects of a project; plans evolve.
3. The time normally available to study a water resources problem is shorter than the time necessary for an adequate state-of-the-art mathematical modeling study, or if there is sufficient time, the objectives of the original study will have significantly shifted by the time the study is completed.

This experience emphasizes not only some of the limitations and difficulties that any water resource systems study may encounter, but more important, it emphasizes the need for constant communication among the analysts, engineers responsible for the systems operations, and policymakers. The success or failure of many past water resource studies is in a large part attributable to the efforts expended or not expended in ensuring adequate and meaningful communication among systems planners, professional engineers responsible for system operation and design, and public officials responsible for major decisions and setting general policies. It is these engineers and public officials, after all, who need the information that can be derived from various models and analyses, and they must have it in a form useful and meaningful to them. At the beginning of any study, objectives are usually poorly defined. As more is learned about what can be gotten, people are better able to identify what they want. Close communication among analysts, engineers, and public officials throughout the modeling process is essential if systems studies are to make their greatest contribution to the planning process.

Furthermore, those who will use the models, and present the information derived from the models to those responsible for making decisions, must be intimately involved with model development, solution, and analysis. Only then can they appreciate the assumptions upon which any particular model is based, and hence adequately evaluate the reliability of the results. Any water resource systems study that involves only outside consultants, and minimal communication between consultants and planners within a responsible management agency, is unlikely to succeed in having a significant impact on the planning process. Models that are useful are alive, constantly being modified and applied by those groups which are responsible for plan preparation, evaluation, and implementation.

1.3 CHARACTERISTICS OF SYSTEMS ANALYSIS APPLICATIONS

Successful systems analysis applications exhibit a number of common characteristics. These are reviewed here because they provide insight into whether a systems study of a particular problem may be worthwhile. If the planners' objectives are very unclear, few alternative courses of action exist, or there is little scientific understanding of the issues involved, then mathematical modeling and sophisticated methodologies are frequently of little use. Successful applications of systems analysis are characterized by:

1. A systems focus or orientation: Attention needs to be and is devoted to the interaction of elements within the system as a whole as well as to the elements themselves.
2. The use of interdisciplinary teams: In many complex and nontraditional problems it is not at all clear from the start what disciplinary viewpoints will turn out to be most appropriate. It is essential that the participants in such work—coming from different established disciplines—become familiar with the techniques, vocabulary, and concepts of the other disciplines. It might be said that participation in interdisciplinary research requires a willingness to make mistakes at the fringes of one's technical competence.
3. The use of formal mathematical models: The overwhelming preference of most systems analysts is to use mathematical models to assist in system description and evaluation and to provide an unambiguous record of the assumptions and data used in the analysis.

Not all water resources planning problems are suitable candidates for study using systems analysis methods. The systems approach is most appropriate when:

4. The system's objectives are reasonably well defined and organizations and individuals can be identified who have the necessary authority and power to implement possible decisions.
5. There are many alternative decisions that may satisfy the stated objectives and the best decision is not obvious.

This text on quantitative planning techniques will be particularly useful for water resources problems which have two additional characteristics:

6. The alternative solutions and the objectives of the system being analyzed are describable by a reasonably tractable mathematical representation.
7. The parameters of the model are estimatable from readily obtainable data.

These last four conditions are, of course, rarely met in practice. In such cases, systems analysis studies may still help in providing new insights and understanding to the problem of concern, but will probably be less successful than would otherwise be the case.

EXERCISES

1-1. What are the characteristics of water resources planning or management problems that are most suitable for analysis using quantitative systems analysis techniques?

1-2. Identify some specific water resource systems planning problems and for each problem specify in words possible objectives, the unknown decision variables whose values need to be determined, and the constraints or relationships that must be met by any solution of the problem.

1-3. From a review of the recent issues of various journals pertaining to water resources and the appropriate areas of engineering, economics, planning and operations research, identify those journals that contain articles on water resource systems planning and analysis, and the topics or problems currently being discussed.

1-4. Many water resource systems planning problems involve considerations that are very difficult if not impossible to quantify, and hence they cannot easily be incorporated into any mathematical model for defining and evaluating various alternative solutions. Briefly discuss what value these admittedly incomplete quantitative models may have in the planning process when nonquantifiable aspects are also important. Can you identify some planning problems that have such intangible objectives?

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