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WATER RESOURCE SYSTEMS PLANNING AND ANALYSIS

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To our teachers, colleagues,
and students throughout the world
who have taught us not only what we know,
but also how much we have yet to learn.

Preface

The constantly increasing demand for a sufficient quantity and quality of water, properly distributed in time and space, has forced engineers and planners to contemplate and propose ever more comprehensive, complex, and ambitious plans for water resource systems. Such plans include the regulation of natural water supplies and the transportation of water between watersheds, river basins, nations, and as it has been suggested, even continents. These projects are undertaken in an attempt to provide water of an adequate quality and quantity at the times and places where it is of sufficient value to justify the effort.

Which of the infinite variety and variations of possible water resource systems and policies should be implemented? Information that can help answer this question is what water resource systems analysts try to provide. Water resource systems analysts use mathematical models and methods to aid engineers, planners, economists, and the public to sort through the myriad of schemes which are and could be proposed. Systems analysis methods can help identify plans or sets of plans and policies that achieve to the greatest extent possible the needs, goals, and aims of those who plan, pay for, and make use of, or are affected by water resource facilities and management plans.

The application of systems methods such as mathematical optimization

and simulation can significantly aid in the definition, evaluation, and selection of water resources investments, designs, and policies. There is increasing use and documentation of systems analysis methods in water resources planning, and courses in water resource systems analysis have become commonplace in graduate and undergraduate programs in engineering schools. This book serves as an introductory text for undergraduate and graduate students in such courses and to practitioners involved in, or responsible for, the planning and management of water resource systems.

Although we have attempted to incorporate into each chapter the current thinking in, and approaches to, water resource systems planning and analysis, this book is not intended to be a review of the literature. Rather, it is intended to introduce readers to the methods useful in water resource systems planning. We have tried to organize the discussion about various quantitative methods for evaluating and comparing alternative water resources projects and plans in a form useful for teaching and self-study. We have generally selected modeling techniques that have seen successful field applications. The tone of the work reflects our conviction that the most useful models for planning are often the simplest, chiefly because they are easy to understand, to explain, and to use. This does not imply that highly sophisticated complex models are less useful. Rather, the analyst should realize that the appropriate model complexity is a compromise between detail and a potential for increased accuracy on the one hand and a savings in model development time, computational requirements, and model simplicity on the other.

Unfortunately, it is difficult to actually teach the practical art of water resource systems analysis in a book such as this and we have declined the temptation to try. In practice, a successful study requires that the system engineers and planners grasp the issues and concerns that are important to those in the planning process, those who will determine the decisions that are made, and those who are directly affected by such decisions. In addition, system engineers and planners must understand the operation of the water system under study including its peculiarities and the alternative courses of action. Then by skillful application and use of models and techniques such as those presented here, the systems engineer can determine and illustrate the important consequences of alternative plans. He or she can identify plans that provide a reasonable compromise among the possibly conflicting objectives of the numerous groups of individuals who are, or will be, involved in or affected by the project. The importance of the art in systems analysis can be grasped from reviewing the various case studies contained in references given throughout the text. However, in practice the art is most likely realized only when diligent, skillful, and open-minded systems engineers ply their trade with honesty, dedication, and the broadest viewpoint possible.

This book requires only an introductory background in calculus, matrix algebra, and probability theory. Chapters 2, 3, and 4 introduce the quanti-

tative methods that form the basis of water resource systems analysis: mathematical programming and simulation, probability and statistics, and benefit-cost analysis and multiobjective modeling. These concepts and methods are discussed in the context of water resources design and management problems.

The application of these quantitative methods form the principal portion of the book. We have made a somewhat artificial but common division of river basin models into water *quantity* and water *quality* models. The modeling approaches to the two problems have significant differences, and at least from a pedagogical viewpoint, there are advantages to separate discussions of water quantity and quality problems when this is possible.

Surface water quantity management problems and models are discussed in four chapters. Chapter 5 treats river basin phenomena as deterministic: future quantities such as streamflows, water requirements, and prices are considered known and certain. Although this is a very simplified view of real water problems, the resulting models are conceptually simple and are adequate for some preliminary planning applications.

Stochastic water quantity models are presented in Chapters 6 and 7. Chapter 6 introduces a variety of synthetic streamflow generating models that can be used to assist in comparing and evaluating proposed or existing water resource systems. Chapter 7 presents a range of stochastic optimization models useful for planning both the design and operation of reservoirs and for solving river basin water allocation problems. These models provide a more realistic representation of the variability of hydrologic elements of water resource systems than do the models in Chapter 5. Stochastic models constitute a more "advanced" topic and require a reasonable understanding of deterministic models and of probability. Finally, Chapter 8 presents some further detail on the water quantity aspects of irrigation planning and operation, an increasingly important activity of water resources planners.

In one sense, water quality management can be viewed as just one of the many purposes to be achieved in river basin planning. However, in many areas of the world, and particularly in developed regions, water pollution control has a very high priority for water resources planning. Chapters 9 and 10 introduce a variety of simulation and optimization models for surface water quality planning. Water quality models are based on mass conservation and descriptions of the biochemical and physical phenomena associated with water pollution. The discussion in these two chapters illustrates how the costs of water quality management alternatives, such as wastewater treatment, flow augmentation, and land disposal of wastewaters, can be incorporated into the models that describe and predict various biochemical and physical phenomena. This provides a means of comparing and evaluating the economic as well as the environmental impacts of various water management alternatives.

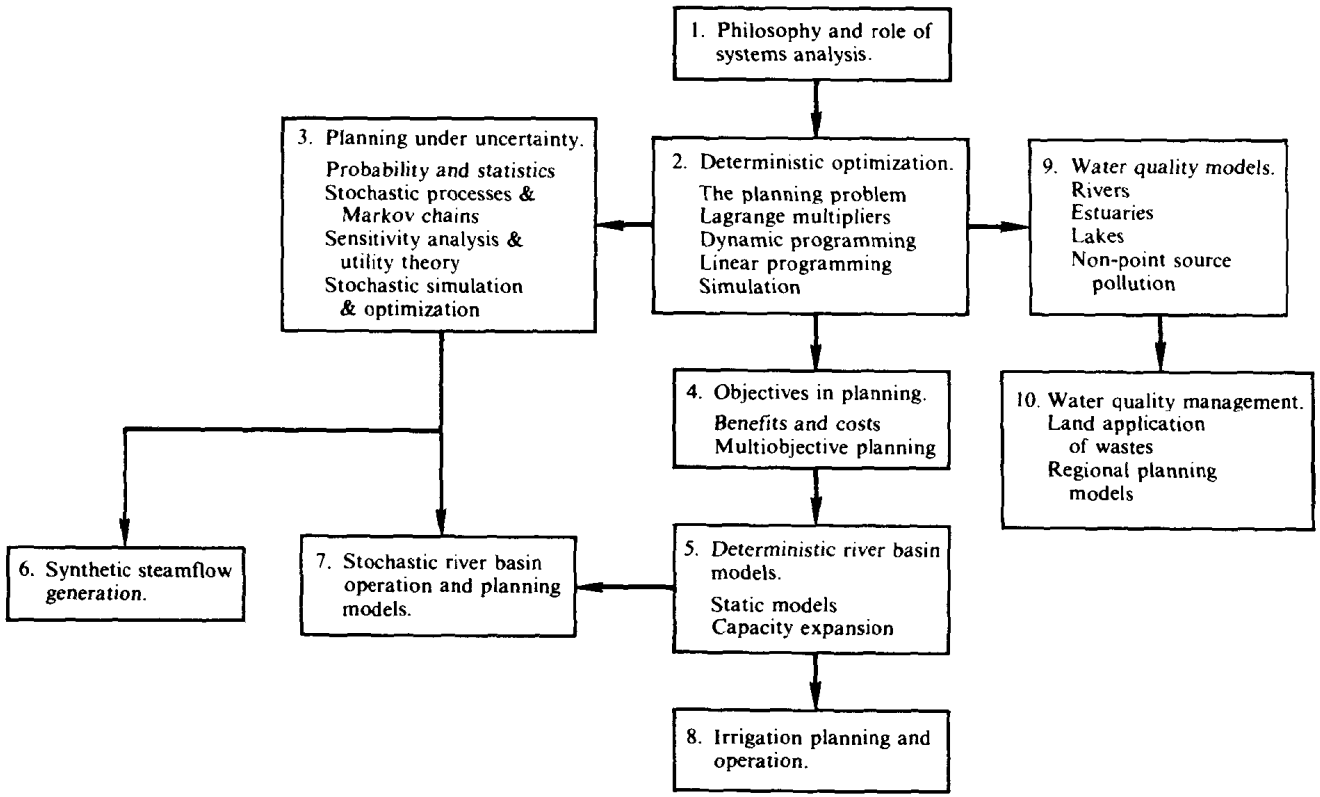

EXHIBIT A. Topics and relationships of chapters.

Exhibit A illustrates the major topics of each chapter. Arrows indicate when the material in one chapter builds upon the material in another chapter. The material may be taught and organized in several ways to meet the needs and interests of an instructor or a reader. We have taught a two-semester course on water resource systems planning. The first semester emphasized deterministic models and methods (Chapters 1, 2, 4, 5, and 8). The second semester addressed stochastic models (Chapters 3, 6, and 7) and water quality problems (Chapters 9 and 10). For those interested primarily in water quality management, Chapters 1, 2, 4, 9, and 10 plus at least Section 5 of Chapter 3 would constitute a good course of study. For instructors whose students have had advanced training in either mathematical programming and optimization or in probability, statistics, and time series analysis, large parts of Chapters 2 and 3 may be covered rapidly. However, we have generally found that going over this material, if only briefly, is useful to the student.

Many individuals helped the authors in the preparation of this book. The authors give special thanks to Helga van der Leeden and Patty Apgar who diligently typed and helped edit many drafts of this book. We must also thank Professor Ir. L.J. Mostertman, Director of the International Institute for Hydraulic and Environmental Engineering, Delft, the Netherlands, and Professors Donald Harleman, David Marks, and Frank Perkins at the Massachusetts Institute of Technology for their financial support and for the opportunity to teach from these notes at their institutes. It is, of course, impossible to recognize and acknowledge the invaluable help of all of our teachers, colleagues, and students at numerous universities and institutes who through their comments and their work have contributed to the production of this book. We particularly thank Stephen Burges, Rolf Deininger, John Dracup, Donald Erlenkotter, Louis Falkson, Warren Hall, James Heaney, Perry McCarty, Gerald Orlob, Sergio Rinaldi, Charles Scherer, Christine Shoemaker, Rodolfo Soncini-Sessa, and Harald Stehfest for their careful reading and criticism of all or parts of earlier drafts. Any remaining errors of fact or opinion are of course solely the responsibility of the other two authors of this book! We would welcome comments from anyone that will help us improve any future editions.

Ithaca, New York

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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 con-