

# Water Resources Systems Planning and Management

An Introduction to Methods, Models  
and Applications

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# Foreword



Within the Netherlands, as in much of the world, the quality of our lives is directly related to the quality of our natural environment – our air, land and water resources. We consider a quality environment crucial to human health and economic and social development as well as for ecosystem preservation and diversity. How well

we manage our natural resources today will determine just how well these resources will serve our descendants and us. Hence, we care much about the management of these resources, especially our water resources.

Many of us in the Netherlands are living in areas that exist only because of the successful efforts of our past water engineers, planners and managers. Managing water in ways that best meet all our diverse needs for water and its protection, including the needs of natural ecosystems, is absolutely essential. But in spite of our knowledge and experience, we Dutch, as others throughout the world, still experience droughts, floods and water pollution. These adverse impacts are not unique to us here in Europe. In too many other regions of this world the need for improved water management is much more critical and much more urgent. Too many people, especially children, suffer each day because of the lack of it.

As we take pride in our abilities to manage water, we also take pride in our abilities to help others manage

water. Institutions such as WL|Delft Hydraulics have been doing this throughout its seventy-five years of existence. This book was written and published, in part, to celebrate its seventy-fifth anniversary.

This book was written by individuals who have simultaneously served as university professors as well as consulting engineers throughout much of their professional careers. They have provided an introduction to practical ways of modeling and analysing water resources systems.

Whether you are studying at a university or working in a developed or developing region, the methods and advice presented in this book can help you develop your skills in the use of quantitative methods of identifying and evaluating effective water resources management plans and policies. It can serve as a guide on ways of obtaining the information you and your organization need when deciding how to best manage these important resources.

This book, introducing an integrated systems approach to water management, can serve many students, teachers, and practising water resource engineers and planners in the years to come.

**His Royal Highness the Prince of Orange  
The Netherlands**

# Preface

Throughout history much of the world has witnessed ever-greater demands for reliable, high-quality and inexpensive water supplies for domestic consumption, agriculture and industry. In recent decades there have also been increasing demands for hydrological regimes that support healthy and diverse ecosystems, provide for water-based recreational activities, reduce if not prevent floods and droughts, and in some cases, provide for the production of hydropower and ensure water levels adequate for ship navigation. Water managers are challenged to meet these multiple and often conflicting demands. At the same time, public stakeholder interest groups have shown an increasing desire to take part in the water resources development and management decision-making process. Added to all these management challenges are the uncertainties of natural water supplies and demands due to changes in our climate, changes in people's standards of living, changes in watershed land uses and changes in technology. How can managers develop, or redevelop and restore, and then manage water resources systems – systems ranging from small watersheds to those encompassing large river basins and coastal zones – in a way that meets society's changing objectives and goals? In other words, how can water resources systems become more integrated and sustainable?

Before engineering projects can be undertaken to address water management problems or to take advantage

of opportunities for increased economic, ecological, environmental and social benefits, they must first be planned. This involves identifying various alternatives for addressing the problems or opportunities. Next, the various impacts of each proposed alternative need to be estimated and evaluated. A variety of optimization and simulation models and modelling approaches have been developed to assist water planners and managers in identifying and evaluating plans. This book introduces the science and art of modelling in support of water resources planning and management. Its main emphasis is on the practice of developing and using models to address specific water resources planning and management problems. This must be done in ways that provide relevant, objective and meaningful information to those who are responsible for making informed decisions about specific issues in specific watersheds or river basins.

Readers of this book are not likely to learn this art of modelling unless they actually employ it. The information, examples and case studies contained in this book, together with the accompanying exercises, we believe, will facilitate the process of becoming a skilled water resources systems modeller, analyst and planner. This has been our profession, and we can highly recommend it to others. Planning and management modelling is a multi-disciplinary activity that is an essential part of almost all projects designed to increase the benefits, however measured,

from available water and related land resources. The modelling and analysis of water resources systems involves science and it also involves people and politics. It is a challenge, but it is also fulfilling.

This book builds on a text titled *Water Resources Systems Planning and Analysis* by Loucks, Stedinger and Haith published by Prentice Hall in 1981. The present work updates much of what was in that text, introduces some new modelling methods that are proving to be useful, and contains considerably more case studies. It benefits considerably from the experiences of WL | Delft Hydraulics, one of the many firms involved around the world using the approaches and methods discussed in this book.

Developments in graphics-based menu-driven interactive computer programs and computer technology during the last quarter of a century have had a significant and beneficial impact on the use of modelling in the practice of water resources engineering, planning and management. All the models discussed in this book are designed for use on micro-computers. The software we use to illustrate the solutions to various problems can be obtained from the Internet free of charge. Commonly available spreadsheet software can also be used. None of this was available in 1981.

Although we have attempted to incorporate into each chapter current approaches to water resources systems planning and analysis, this book does not pretend to be a review of the state-of-the-art of water resources systems analysis found in the literature. Rather it is intended to introduce readers to some of the more commonly used models and modelling approaches applied to the planning and managing of water resources systems. We have tried to organize our discussion of these topics in a way useful for teaching and self-study. The contents reflect our belief that the most appropriate methods for planning and management are often the simpler ones, chiefly because they are easier to understand and explain, require less input data and time, and are easier to apply to specific issues or problems. This does not imply that more sophisticated and complex models are less useful. Sometimes their use is the only way one can provide the needed information. In this book, we attempt to give readers the knowledge to make appropriate choices regarding model complexity. These choices will depend in part on factors such as the issues being addressed and the information

needed, the level of accuracy desired, the availability of data and their cost, and the time required and available to carry out the analysis. While many analysts have their favourite modelling approach, the choice of model should be based on a knowledge of various modelling approaches and their advantages and limitations.

This book assumes readers have had some mathematical training in algebra, calculus, geometry and the use of vectors and matrices. Readers of Chapters 7 through 9 will benefit from some background in probability and statistics. Similarly, some exposure to micro-economic theory and welfare economics will be useful for readers of Chapter 10. Some knowledge of hydrology, hydraulics and environmental engineering will also be beneficial, but not absolutely essential. Readers wanting an overview of some of natural processes that take place in watersheds, river basins, estuaries and coastal zones can refer to Appendix A. An introductory course in optimization and simulation methods, typically provided in either an operations research or an economic theory course, can also benefit the reader, but again it is not essential.

Chapter 1 introduces water resources systems planning and management and describes some examples of water resources systems projects in which modelling has had a critical role. These example projects also serve to identify some of the current issues facing water managers in different parts of the world. Chapter 2 defines the modelling approach in general and the role of models in water resources planning and management projects. Chapter 3 begins the discussion of optimization and simulation modelling methods and how they are applied and used in practice. It also discusses how modelling activities in water resources development, planning and/or management projects should be managed.

Chapter 4 is devoted to optimization modelling. This relatively large chapter focuses on the use of various optimization methods for the preliminary definition of infrastructure design and operating policies. These preliminary results define alternatives that usually need to be further analysed and improved using simulation methods. The advantages and limitations of different optimization approaches are presented and illustrated using some simple water allocation, reservoir operation and water quality management problems. Chapter 5 extends this discussion of optimization to problems characterized by 'fuzzy' (more qualitative) objectives.

Chapter 6 introduces some of the more recently developed methods of statistical modelling, including artificial neural networks and evolutionary search methods including genetic algorithms. This chapter expects interested readers will refer to other books, many of which are solely devoted to just these topics, for more detail.

Chapters 7 through 9 are devoted to probabilistic models, uncertainty and sensitivity analyses. These methods are useful not only for identifying more realistic infrastructure designs and operating policies given hydrological variability and uncertain parameter values and objectives, but also for estimating some of the major uncertainties associated with model predictions. Such probabilistic and stochastic models can also help identify just what model input data are needed and how accurate those data need be with respect to their influence on the decisions being considered.

Water resources planning and management today inevitably involve multiple goals or objectives, many of which may be conflicting. It is difficult, if not impossible, to please all stakeholders all the time. Models containing multiple objectives can be used to identify the tradeoffs among conflicting objectives. This is information useful to decision-makers who must decide what the best tradeoffs should be, both among conflicting objectives and among conflicting stakeholder interest groups. Multi-objective modelling, Chapter 10, identifies various types of economic, environmental and physical objectives, and some commonly used ways of including multiple objectives in optimization and simulation models.

Chapter 11 is devoted to various approaches for modelling the hydrological processes in river basins. The focus is on water quantity prediction and management. This is followed by Chapter 12 on the prediction and management of water quality processes in river basins and Chapter 13 on the prediction and management of water quantity and quality in storm water runoff, water supply distribution and treatment, and wastewater collection and treatment in urban areas. The final Chapter (Chapter 14) provides a synopsis, reviewing again the main role of models, introducing measures that can be used to evaluate their usefulness in particular projects, and presenting some more case studies showing the application of models to water resources management issues and problems.

Following these fourteen chapters are five appendices. They contain descriptions of A) natural hydrological and

ecological processes in river basins, estuaries and coastal zones, B) monitoring and adaptive management, C) drought management, D) flood management, and E) a framework for assessing, developing and managing water resources systems as practiced by WL | Delft Hydraulics.

We believe Chapters 1 through 4 are useful prerequisites to most of the remaining chapters. For university teachers, the contents of this book represent more than can normally be covered in a single quarter or semester course. A first course can include Chapters 1 through 4, and possibly Chapters 10, 11 or 13 in addition to Chapter 14, depending on the background of the participants in the class. A second course could include Chapters 7 through 9 and/or any combination of Chapters 5, 6, 12, 13 or 14, as desired. Clearly much depends on the course objectives and on the background knowledge of the course participants. Some exercises for each chapter are included in the attached CD. (Instructors may write to the authors to obtain suggested solutions to these exercises.)

The writing of this book began at WL | Delft Hydraulics as a contribution to its seventy-fifth anniversary. We are most grateful for the company's support, both financial and intellectual. While this book is not intended to be a testimony to Delft Hydraulics' contributions to the development and application of models to water resources planning and management projects, it does reflect the approaches taken, and modelling tools used by them and other such firms and organizations that engage in water resources planning, development and management projects worldwide.

Many have helped us prepare this book. Jery Stedinger wrote much of Chapters 7, 8 and 9, Nicki Villars helped substantially with Chapter 12, and Jozef Dijkman contributed a major portion of Appendix D. Vladam Babovic, Henk van den Boogaard, Tony Minns, and Arthur Mynett contributed material for Chapter 6. Roland Price provided material for Chapter 13. Others who offered advice and who helped review earlier chapter drafts include Martin Baptist, Herman Breusers, Harm Duel, Herman Gerritsen, Peter Gijsbers, Jos van Gils, Simon Groot, Karel Heynert, Joost Icke, Hans Los, Marcel Marchand, Erik Mosselman, Erik Ruijgh, Johannes Smits, Mindert de Vries and Micha Werner. Ruud Ridderhof and Engelbert Vennix created the figures and tables in this book. We thank all these individuals and others, including our students, who

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Most importantly we wish to acknowledge and thank all our teachers, students and colleagues throughout the world who have taught us all we know and added to the quality of our professional and personal lives. We have tried our best to make this book error free, but inevitably somewhere there will be flaws. For that we apologize and take responsibility for any errors of fact, judgment or science that may be contained in this book. We will be most grateful if you let us know of any or have other suggestions for improving this book.

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# Introduction

Water resources are special. In their natural states they are beautiful. People like to live and vacation near rivers, lakes and coasts. Water is also powerful. Water can erode rock, alter existing landscapes and form new ones. Life on this planet depends on water. Most of our economic activities consume water. All of the food we grow, process and eat requires water. Much of our waste is transported and assimilated by water. The importance of water to our well-being is beyond question. Our dependence on water will last forever.

So, what is the problem? The answer is simply that water, although plentiful, is not distributed as we might wish. There is often too much or too little, or what exists is too polluted or too expensive. A further problem is that the overall water situation is likely to further deteriorate as a result of global changes. This is a result not only of climatic change but also of other global change drivers such as population growth, land use changes, urbanization and migration from rural to urban areas, all of which will pose challenges never before seen. Water obviously connects all these areas and any change in these drivers has an impact on it. Water has its own dynamics that are fairly non-linear. For example, while population growth in the twentieth century increased three-fold – from 1.8 billion to 6 billion people – water withdrawal during the same period increased six-fold! That is clearly unsustainable. Freshwater, although a renewable resource, is finite

and is very vulnerable. If one considers all the water on Earth, 97.5% is located in the seas and oceans and what is available in rivers, lakes and reservoirs for immediate human consumption comprises no more than a mere 0.007 per cent of the total. This is indeed very limited and on average is roughly equivalent to 42,000 cubic kilometres per year.

If one looks at the past thirty years only in terms of reduction in per capita water availability in a year the picture is even more disturbing. While in 1975 availability stood at around 13,000 cubic metres per person per year, it has now dropped to 6,000 cubic metres; meanwhile water quality has also severely deteriorated. While this cannot be extrapolated in any meaningful manner, it nevertheless indicates the seriousness of the situation. This will likely be further exacerbated by the expected impacts of climate change. Although as yet unproven to the required rigorous standards of scientific accuracy, increasing empirical evidence indicates that the hydrological cycle is accelerating while the amount of water at a given moment in time remains the same. If this acceleration hypothesis is true then it will cause an increase in the frequency and magnitude of flooding. At the other end of the spectrum, the prevailing laws of continuity mean that the severity and duration of drought will also increase. These increased risks are likely to have serious regional implications. Early simulation studies,

carried out by IHP, suggest that wet areas will become even more humid while dry areas will become increasingly arid. This will not occur overnight; similarly, appropriate countermeasures will need time to establish policies that integrate the technical and social issues in a way that takes appropriate consideration of the cultural context.

Tremendous efforts and political will are needed to achieve the two water related Millennium Development Goals (MDGs), that is, to halve the number of human beings who have no access to safe drinking water and adequate sanitation facilities respectively, by 2015. In the case of drinking water, we have 1.2 billion fellow human beings that have no access to safe drinking water, while in the case of sanitation, the figure is 2.4 billion.

The substantial growth of human populations – especially as half of humanity already lives in urban areas – and the consequent expansion of agricultural and industrial activities with a high water demand, have only served to increase problems of water availability, quality – and in many regions – waterborne disease. There is now an increasing urgency in the UN system to protect water resources through better management. Data on the scale of deforestation with subsequent land use conversion, soil erosion, desertification, urban sprawl, loss of genetic diversity, climate change and the precariousness of food production through irrigation, all reveal the growing seriousness of the problem. We have been forced to recognize that society's activities can no longer continue unchecked without causing serious damage to the very environment and ecosystems we depend upon for our survival. This is especially critical in water scarce regions, many of which are found in the developing world and are dependent on water from aquifers that are not being recharged as fast as their water is being withdrawn and consumed. Such practices are clearly not sustainable.

Proper water resources management requires consideration of both supply and demand. The mismatch of supply and demand over time and space has motivated the development of much of the water resources infrastructure that is in place today. Some parts of the globe witness regular flooding as a result of monsoons and torrential downpours, while other areas suffer from

the worsening of already chronic water shortages. These conditions are often aggravated by the increasing discharge of pollutants resulting in a severe decline in water quality.

The goal of sustainable water management is to promote water use in such a way that society's needs are both met to the extent possible now and in the future. This involves protecting and conserving water resources that will be needed for future generations. UNESCO's International Hydrological Programme (IHP) addresses these short- and long-term goals by advancing our understanding of the physical and social processes affecting the globe's water resources and integrating this knowledge into water resources management. This book describes the kinds of problems water managers can and do face and the types of models and methods one can use to define and evaluate alternative development plans and management policies. The information derived from these models and methods can help inform stakeholders and decision-makers alike in their search for sustainable solutions to water management problems. The successful application of these tools requires collaboration among natural and social scientists and those in the affected regions, taking into account not only the water-related problems but also the social, cultural and environmental values.

On behalf of UNESCO it gives me great pleasure to introduce this book. It provides a thorough introduction to the many aspects and dimensions of water resources management and presents practical approaches for analysing problems and identifying ways of developing and managing water resources systems in a changing and uncertain world. Given the practical and academic experience of the authors and the contributions they have made to our profession, I am confident that this book will become a valuable asset to those involved in water resources planning and management. I wish to extend our deepest thanks to Professors Pete Loucks and Eelco van Beek for offering their time, efforts and outstanding experience, which is summarized in this book for the benefit of the growing community of water professionals.

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