Water Resource Systems Planning and Management
Water Resource Systems Planning and Management
An Introduction to Methods, Models, and Applications

With Contributions by
Jery R. Stedinger · Jos P.M. Dijkman · Monique T. Villars
Foreword

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 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 nonlinear. For example, while population growth in the twentieth century increased threefold—from 1.8 to 6 billion people—water withdrawal during the same period increased sixfold! 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 % of the total. This is indeed very limited and on average is roughly equivalent to 42,000 km³ per year.

If one looks at the past 30 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 m³ per person per year, it has now dropped to 6000 m³; 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 implica-
tions. Early simulation studies 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 substantially reduce
the number of human beings who have no access to safe drinking water and
adequate sanitation facilities respectively. 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 avail-
ability, 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 Pro-
gramme (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 analyzing 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 Profs. 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.

András Szöllösi-Nagy
Past Deputy Assistant Director-General, UNESCO
and Past Secretary, International Hydrological Programme
Past Rector Magnificus, UNESCO-IHE, Delft, The Netherlands
Preface

Water resource systems planning and management issues are rarely simple. Demands for reliable supplies of clean water to satisfy the energy, food, and industrial demands of an increasing population and to maintain viable natural ecosystems are growing. This is happening at the same time changes in our climate are increasing the risks of having to deal with too little or too much water in many river basins, watersheds, and urban areas. Societies are becoming increasingly aware of the importance of water and its management and use; their governing institutions are becoming increasingly involved in water resources development and management decision-making processes.

To gain a better understanding of the complex interactions among all the hydrologic, ecologic, economic, engineering and social components of water resource systems, analyses based on systems perspectives are useful. While analyses of such complex systems can be challenging, integrated systems approaches are fundamental for identifying and evaluating options for improving system performance and security for the benefit of all of us.

Just how well we are able to plan and manage our water availability, quality, and variability is a major determinant of the survival of species, the functioning and resilience of ecosystems, the strength of economies, and the vitality of societies. To aid in the analysis of planning and managing options, a variety of modelling approaches have been developed. This book introduces the science and art of developing and applying various modelling approaches 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 issues and problems. Their purpose is to provide relevant, objective, timely and meaningful information to those who are responsible for deciding how we develop, manage, and use our water resources.

Readers of this book are not likely to learn the art of systems modelling and analyses unless they actually do it. The modelling approaches, examples and case studies contained in this book, together with the exercises offered at the end of most chapters, we believe and hope, will facilitate the process of becoming a skilled water resources systems modeler, analyst and planner. This has been our profession, indeed our hobby and source of enjoyment, and we can highly recommend it to others.

Water resource systems planning and management is a multidisciplinary activity. The modelling and analysis of water resources systems involves
inputs from the applicable natural and social sciences and from the people, the stakeholders, who will be impacted. It is a challenge.

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. Rather it is intended to introduce readers to the art of developing and using models and modelling approaches applied to the planning and managing of water resources systems. We have tried to organize our discussion 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 approaches, the choice of a particular model and solution method should be based on the knowledge of various modelling approaches and their advantages and limitations. There is no one best approach for analyzing all the issues one might face in this profession.

This book assumes readers have had some mathematical training in algebra, calculus, geometry and the use of vectors and matrices. Readers will also benefit from some background in probability and statistics and some exposure to micro-economic theory and welfare economics. 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 the Appendices (available on the internet along with the book itself). 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 reviews some examples of water resources systems projects in which modelling has had a critical role. These projects also serve to identify some of the current issues facing water managers in different parts of the world. Chapter 2 introduces the general modelling approach and the role of models in water resources planning and management activities. Chapter 3 begins the discussion of optimization and simulation modelling and how they are applied and used in practice. Chapter 4 focuses on the development and 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 analyzed and improved using simulation methods. The advantages and limitations of different
optimization/simulation approaches are illustrated using some simple water allocation, reservoir operation and water quality management problems.

Chapter 5 extends this discussion of optimization to problems characterized by more qualitative objectives and/or constraints. In addition, it introduces some of the more recently developed methods of statistical modelling, including artificial neural networks and evolutionary search methods including genetic algorithms and genetic programming. This chapter expects interested readers desiring more detail will refer to other books and papers, many of which are solely devoted to just these topics. Chapters 6 through 8 are devoted to probabilistic models, uncertainty and sensitivity analyses. These methods are useful not only for identifying more realistic, reliable, and robust infrastructure designs and operating policies for the 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 the information useful to decision-makers who must decide what to do given these tradeoffs among conflicting performance criteria that stakeholders care about. Chapter 9 on multi-objective modelling identifies various types of economic, environmental and physical objectives, and some commonly used ways of including multiple objectives in optimization and simulation models.

Chapter 10 is devoted to various approaches for modelling water quality in surface water bodies. Chapter 11 focuses on modelling approaches for multiple purpose water quantity planning and management in river basins. Chapter 12 zooms into urban areas and presents some ways of analyzing urban water systems. Finally, Chap. 13 describes how projects involving the analyses of water resource systems can be planned and executed.

Following these thirteen chapters are four appendices. They are not contained in the book but are available on the internet where this book can be downloaded. 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, and (D) flood management.

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 might include Chaps. 1 through 5, and possibly Chaps. 9 and 10 or 11 or 12 or 13 depending on the background and interest of the participants in the class. A second course could include Chaps. 6 through 8 and/or any combination of Chaps. 10 through 12, as desired. Exercises are offered at the end of each chapter, and instructors using this text in their academic courses can contact the authors for the solutions of those exercises if desired.
Many have helped us prepare this book. Jery Stedinger contributed to Chaps. 6, 7 and 8, Nicki Villars helped substantially with Chap. 10, and Jozef Dijkman contributed a major portion related to flood management. Tjitte Nauta, Laura Basco Carrera and Thijs Stoffelen contributed to Chap. 13. Others who offered advice and who helped review earlier chapter drafts include Vladan Babovic, Martin Baptist, Henk van den Boogaard, Herman Breusers, Harm Dael, Herman Gerritsen, Peter Gijsbers, Jos van Gils, Simon Groot, Karel Heynert, Joost Icke, Hans Los, Marcel Marchand, Tony Minns, Erik Moselman, Arthur Mynett, Roland Price, Erik Ruijgh, Johannes Smits, Mindert de Vries and Micha Werner. Engelbert Vennix and Hans van Ber gem created most of the figures and tables in this book. We again thank Deltas and all these individuals and others who provided assistance and support on various aspects during the entire time in 2005 and when this second edition was being prepared.

We have also benefited from the comments of Profs. Jan-Tai Kuo at National Taiwan University in Taipei, Jay Lund at the University of California at Davis, Daene McKinney of the University of Texas in Austin, Peter Rogers at Harvard University in Cambridge, MA, Tineke Ruijgh-van der Ploeg at TU-Delft, Robert Traver at Villanova University in Philadelphia, and Jinwen Wang at Huazhong University of Science and Technology in Wuhan, all of whom have used earlier drafts of this book in their classes. Finally we acknowledge with thanks the critical support of Andras Szollösi-Nagy, recently retired as rector of UNESCO-IHE in Delft, NL, and the publishing staff at UNESCO for publishing the first edition of this book and making its electronic version free and unrestricted. We are especially grateful to Michael Luby of Springer for all his assistance and guidance, and to Deltas and UNESCO-IHE in Delft, NL, for sharing the cost of publishing this second edition. We have written this book for an international audience, and hence we are especially grateful and pleased to have this connection to and support from Deltas and UNESCO-IHE.

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.

Ithaca, NY, USA  
Delft, The Netherlands

Daniel P. Loucks  
Eelco van Beek

July 2016
## Contents

1 Water Resources Planning and Management: An Overview ....................................... 1

1.1 Introduction ............................................ 1

1.2 Planning and Management Issues: Some Case Studies ..................................... 2

1.2.1 Kurds Seek Land, Turks Want Water .......... 3

1.2.2 Sharing the Water of the Jordan River Basin: Is There a Way? ................. 5

1.2.3 Mending the “Mighty and Muddy” Missouri ........................................ 6

1.2.4 The Endangered Salmon ......................................... 8

1.2.5 Wetland Preservation: A Groundswell of Support and Criticism ............. 10

1.2.6 Lake Source Cooling: Aid to Environment, or Threat to Lake? .............. 10

1.2.7 Managing Water in the Florida Everglades ....................................... 12

1.2.8 Restoration of Europe’s Rivers and Seas ..................................... 14

1.2.9 Flood Management on the Senegal River ....................................... 19

1.2.10 Nile Basin Countries Striving to Share Its Benefits .................................. 20

1.2.11 Shrinking Glaciers at Top of the World .................................. 22

1.2.12 China, a Thirsty Nation ........................................... 22

1.2.13 Managing Sediment in China’s Yellow River ..................................... 23

1.2.14 Damming the Mekong (S.E. Asia), the Amazon, and the Congo .......... 23

1.3 So, Why Plan, Why Manage? ............................................ 28

1.3.1 Too Little Water ............................................ 30

1.3.2 Too Much Water ............................................ 31

1.3.3 Too Polluted ............................................... 31

1.3.4 Too Expensive ............................................. 32

1.3.5 Ecosystem Too Degraded ............................................. 32

1.3.6 Other Planning and Management Issues ..................................... 33

1.4 System Planning Scales ............................................. 33

1.4.1 Spatial Scales for Planning and Management ..................................... 33

1.4.2 Temporal Scales for Planning and Management ..................................... 34
1.5 Planning and Management Approaches .......................... 34
1.5.1 Top-Down Planning and Management ................. 34
1.5.2 Bottom-Up Planning and Management ............. 34
1.5.3 Integrated Water Resources Management .............. 36
1.5.4 Water Security and the Sustainable Development Goals (SDGs) ............ 36
1.5.5 Planning and Management Aspects ...................... 37
1.6 Planning and Management Characteristics ................. 40
1.6.1 Integrated Policies and Development Plans ........... 40
1.6.2 Sustainability ........................................ 42
1.7 Meeting the Planning and Management Challenges—A Summary .................. 43
References .................................................. 45
Exercises .................................................. 48

2 Water Resource Systems Modeling: Its Role in Planning and Management .................. 51
2.1 Introduction .......................................... 51
2.2 Modeling Water Resource Systems ......................... 53
  2.2.1 An Example Modeling Approach ....................... 54
  2.2.2 Characteristics of Problems to be Modeled ............ 55
2.3 Challenges Involving Modeling .............................. 57
  2.3.1 Challenges of Planners and Managers .................. 57
  2.3.2 Challenges of Modelers ............................... 58
  2.3.3 Challenges of Applying Models in Practice .......... 60
  2.3.4 Evaluating Modeling Success .......................... 61
2.4 Developments in Modeling ................................ 62
  2.4.1 Technology ........................................ 62
  2.4.2 Algorithms ........................................ 63
  2.4.3 Interactive Model-Building Environments .......... 63
  2.4.4 Open Modeling Systems ............................ 68
2.5 Conclusions ........................................... 69
References .................................................. 70
Exercises .................................................. 71

3 Models for Identifying and Evaluating Alternatives ......... 73
3.1 Introduction .......................................... 73
  3.1.1 Model Components ................................ 74
3.2 Plan Formulation and Selection ............................ 75
  3.2.1 Plan Formulation .................................. 76
  3.2.2 Plan Selection ..................................... 78
3.3 Conceptual Model Development ............................. 80
3.4 Simulation and Optimization ............................... 81
  3.4.1 Simulating a Simple Water Resources System .......... 82
  3.4.2 Defining What to Simulate ......................... 84
  3.4.3 Simulation Versus Optimization .................... 85
3.5 Conclusions ........................................... 86
Reference .................................................. 87
Exercises .................................................. 88
4 An Introduction to Optimization Models and Methods

4.1 Introduction

4.2 Comparing Time Streams of Economic Benefits and Costs

4.2.1 Interest Rates

4.2.2 Equivalent Present Value

4.2.3 Equivalent Annual Value

4.3 Nonlinear Optimization Models and Solution Procedures

4.3.1 Solution Using Calculus

4.3.2 Solution Using Hill Climbing

4.3.3 Solution Using Lagrange Multipliers

4.4 Dynamic Programming

4.4.1 Dynamic Programming Networks and Recursive Equations

4.4.2 Backward-Moving Solution Procedure

4.4.3 Forward-Moving Solution Procedure

4.4.4 Numerical Solutions

4.4.5 Dimensionality

4.4.6 Principle of Optimality

4.4.7 Additional Applications

4.4.8 General Comments on Dynamic Programming

4.5 Linear Programming

4.5.1 Reservoir Storage Capacity-Yield Models

4.5.2 A Water Quality Management Problem

4.5.3 A Groundwater Supply Example

4.5.4 A Review of Linearization Methods

4.6 A Brief Review

5 Data-Fitting, Evolutionary, and Qualitative Modeling

5.1 Introduction

5.2 Artificial Neural Networks

5.2.1 The Approach

5.2.2 An Example

5.3 Evolutionary Algorithms

5.3.1 Genetic Algorithms

5.3.2 Example Iterations

5.3.3 Differential Evolution

5.3.4 Covariance Matrix Adaptation Evolution Strategy

5.4 Genetic Programming

5.5 Qualitative Functions and Modeling

5.5.1 Linguistic Functions

5.5.2 Membership Functions

5.5.3 Illustrations of Qualitative Modeling
6 An Introduction to Probability, Statistics, and Uncertainty

6.1 Introduction ........................................................................ 213

6.2 Probability Concepts and Methods ........................................ 215
  6.2.1 Random Variables and Distributions ......................... 215
  6.2.2 Expected Values ......................................................... 218
  6.2.3 Quantiles, Moments, and Their Estimators .................. 219
  6.2.4 L-Moments and Their Estimators .................................. 224

6.3 Distributions of Random Events ......................................... 225
  6.3.1 Parameter Estimation ................................................... 227
  6.3.2 Model Adequacy ......................................................... 230
  6.3.3 Normal and Lognormal Distributions ......................... 234
  6.3.4 Gamma Distributions .................................................. 237
  6.3.5 Log-Pearson Type 3 Distribution ................................... 239
  6.3.6 Gumbel and GEV Distributions .................................... 241
  6.3.7 L-Moment Diagrams ................................................... 244

6.4 Analysis of Censored Data ................................................ 245

6.5 Regionalization and Index-Flood Method ............................ 247

6.6 Partial Duration Series ...................................................... 249

6.7 Stochastic Processes and Time Series ................................. 250
  6.7.1 Describing Stochastic Processes .................................... 250
  6.7.2 Markov Processes and Markov Chains ......................... 251
  6.7.3 Properties of Time Series Statistics .............................. 254

6.8 Synthetic Streamflow Generation ....................................... 257
  6.8.1 Introduction ............................................................. 257
  6.8.2 Streamflow Generation Models .................................... 260
  6.8.3 A Simple Autoregressive Model ................................... 261
  6.8.4 Reproducing the Marginal Distribution ....................... 263
  6.8.5 Multivariate Models ................................................... 265
  6.8.6 Multiseason, Multisite Models ..................................... 267

6.9 Stochastic Simulation ......................................................... 270
  6.9.1 Generating Random Variables ..................................... 271
  6.9.2 River Basin Simulation ............................................... 272
  6.9.3 The Simulation Model ............................................... 273
  6.9.4 Simulation of the Basin .............................................. 274
  6.9.5 Interpreting Simulation Output ..................................... 275

6.10 Conclusions ................................................................. 281

References ................................................................. 287

Exercises ................................................................. 289

7 Modeling Uncertainty .......................................................... 301

7.1 Introduction ................................................................. 301

7.2 Generating Values from Known Probability Distributions .... 302

7.3 Monte Carlo Simulation .................................................. 304
## Contents

7.4 Chance Constrained Models .......................... 306
7.5 Markov Processes and Transition Probabilities ....... 308
7.6 Stochastic Optimization ............................... 311
  7.6.1 Probabilities of Decisions ......................... 316
  7.6.2 A Numerical Example ............................. 317
7.7 Summary .............................................. 327
Reference .................................................. 327
Exercises .................................................. 328

8 System Sensitivity and Uncertainty Analysis ............ 331
  8.1 Introduction ....................................... 331
  8.2 Issues, Concerns, and Terminology .................. 332
  8.3 Variability and Uncertainty in Model Output ....... 334
    8.3.1 Natural Variability ............................. 336
    8.3.2 Knowledge Uncertainty ......................... 337
    8.3.3 Decision Uncertainty ............................ 338
  8.4 Sensitivity and Uncertainty Analyses ................. 339
    8.4.1 Uncertainty Analyses ........................... 339
    8.4.2 Sensitivity Analyses ............................ 344
  8.5 Performance Indicator Uncertainties ................ 362
    8.5.1 Performance Measure Target Uncertainty ....... 362
    8.5.2 Distinguishing Differences Between
      Performance Indicator Distributions ............. 366
  8.6 Communicating Model Output Uncertainty .............. 367
  8.7 Conclusions ....................................... 370
References ............................................... 371
Exercises ............................................... 373

9 Performance Criteria .................................... 375
  9.1 Introduction ....................................... 375
  9.2 Informed Decision-Making ........................... 376
  9.3 Performance Criteria and General Alternatives ....... 377
    9.3.1 Constraints on Decisions ....................... 378
    9.3.2 Tradeoffs Among Performance Criteria ......... 379
  9.4 Quantifying Performance Criteria .................... 380
    9.4.1 Economic Criteria .............................. 380
    9.4.2 Environmental Criteria .......................... 389
    9.4.3 Ecological Criteria ............................. 389
    9.4.4 Social Criteria ................................. 392
  9.5 Multicriteria Analyses .............................. 393
    9.5.1 Dominance ..................................... 394
    9.5.2 The Weighting Method ........................... 395
    9.5.3 The Constraint Method ........................... 396
    9.5.4 Satisficing .................................... 398
    9.5.5 Lexicography ................................... 398
    9.5.6 Indifference Analysis ............................ 399
    9.5.7 Goal Attainment ................................ 400
## 10 Water Quality Modeling and Prediction

10.1 Introduction ................................................. 417
10.2 Establishing Ambient Water Quality Standards .......... 418
10.2.1 Water Use Criteria. ........................................ 419
10.3 Water Quality Model Use ..................................... 420
10.3.1 Model Selection Criteria. ................................. 421
10.3.2 Model Chains ............................................... 422
10.3.3 Model Data .................................................. 423
10.4 Models of Water Quality Processes ....................... 425
10.4.1 Mass Balance Principles .................................. 425
10.4.2 Steady-State Models ....................................... 428
10.4.3 Design Streamflows for Setting and Evaluating Quality Standards ............................................ 430
10.4.4 Temperature ................................................. 432
10.4.5 Sources and Sinks ......................................... 433
10.4.6 First-Order Constituents ................................... 433
10.4.7 Dissolved Oxygen ........................................... 433
10.4.8 Nutrients and Eutrophication ............................. 437
10.4.9 Toxic Chemicals ............................................ 441
10.4.10 Sediments .................................................. 446
10.4.11 Processes in Lakes and Reservoirs .................... 446
10.5 Simulation Methods .......................................... 452
10.5.1 Numerical Accuracy ........................................ 452
10.5.2 Traditional Approach ....................................... 453
10.5.3 Backtracking Approach ..................................... 455
10.5.4 Model Uncertainty .......................................... 457
10.6 Conclusions—Implementing a Water Quality Management Policy ............................................. 458
References ......................................................... 459
Exercises .......................................................... 462

## 11 River Basin Modeling

11.1 Introduction .................................................. 469
11.2 Model Time Periods ........................................... 470
11.3 Streamflow Estimation ....................................... 471
11.4 Streamflow Routing .......................................... 472
13.3 Conceptual Description of WRS
13.3.1 Characteristics of the Natural Resources System
13.3.2 Characteristics of the Socioeconomic System
13.3.3 Characteristics of the Administrative and Institutional System

13.4 Framework for Analysis and Implementation
13.4.1 Step I—Inception Phase
13.4.2 Step II—Situation Analysis
13.4.3 Step III—Strategy Building
13.4.4 Steps IV and V—Action Planning and Implementation

13.5 Making It Work
13.5.1 Stakeholder Engagement
13.5.2 Using Models in a Planning Process

13.6 Conclusions

References

Index