

Handbook of Applied Hydrology

Second Edition



Vijay P. Singh
Editor-in-Chief

Handbook of Applied Hydrology

Editor-in-Chief

Vijay P. Singh, Ph.D., D.Sc., D. Eng. (Hon.), Ph.D. (Hon.), D. Sc. (Hon.), P.E., P.H., Hon. D. WRE, Academician (GFA), is a Distinguished Professor and Caroline & William N. Lehrer Distinguished Chair in Water Engineering in the Department of Biological and Agricultural Engineering and Zachry Department of Civil Engineering at Texas A&M University. He holds a B.Tech degree from U.P. University of Agriculture and Technology, a Master's Degree from the University of Guelph, a Ph.D. from Colorado State University, and a D.Sc. from the University of the Witwatersrand. One of today's leading experts in the field of hydrology, Dr. Singh specializes in surface water hydrology, groundwater hydrology, hydraulics, irrigation engineering, environmental quality, and water resources. He has published 25 books and has edited over 58 books, and has published hundreds of journal articles. He has been the Editor-in-Chief of the Journal of Hydrologic Engineering, ASCE; is currently serving as Editor-in-Chief of Open Agriculture, and Journal of Agricultural research, and Journal of Groundwater Research and is on the editorial boards of numerous journals. He is also serving as Editor-in-Chief of Water Science and Technology Book Series as well as World Water Resources Book series. He has received more than 75 national and international awards.

Handbook of Applied Hydrology

EDITED BY VIJAY P. SINGH

Second Edition to replace the classic 1963 edition edited by Ven Te Chow



New York Chicago San Francisco Athens London
Madrid Mexico City Milan New Delhi
Singapore Sydney Toronto

Cataloging-in-Publication Data is on file with the Library of Congress.
McGraw-Hill Education books are available at special quantity discounts to use as premiums and sales promotions, or for use in corporate training programs. To contact a representative please visit the Contact Us page at www.mhprofessional.com.

Handbook of Applied Hydrology, Second Edition

Copyright ©2017 by McGraw-Hill Education. All rights reserved. Printed in the United States of America.
Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a data base or retrieval system, without the prior written permission of the publisher.

1 2 3 4 5 6 7 8 9 DOW 21 20 19 18 17 16

ISBN 978-0-07-183509-1
MHID 0-07-183509-1

The pages within this book were printed on acid-free paper.

Sponsoring Editor

Lauren Poplawski

Copy Editor

Cenveo® Publisher Services

Editorial Supervisor

Donna M. Martone

Proofreader

Cenveo® Publisher Services

Acquisitions Coordinator

Lauren Rogers

Indexer

Ariel O. Tuplano

Project Manager

Raghavi Khullar, Cenveo®
Publisher Services

Production Supervisor

Pamela A. Pelton

Composition Art Director, Cover

Jeff Weeks

Information contained in this work has been obtained by McGraw-Hill Education from sources believed to be reliable. However, neither McGraw-Hill Education nor its authors guarantee the accuracy or completeness of any information published herein, and neither McGraw-Hill Education nor its authors shall be responsible for any errors, omissions, or damages arising out of use of this information. This work is published with the understanding that McGraw-Hill Education and its authors are supplying information but are not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought.

Dedicated to
Hydrologists and Water Scientists

Contents in Brief

Part 1	Fundamentals	1-1
Part 2	Data Collection and Processing	4-1
Part 3	Methods	11-1
Part 4	Hydrologic Processes and Modeling	37-1
Part 5	Sediment and Pollutant Transport	63-1
Part 6	Hydrometeorologic and Hydrologic Extremes	72-1
Part 7	Systems Hydrology	81-1
Part 8	Hydrology of Large Rivers and Lake Basins	93-1
Part 9	Applications and Design	125-1
Part 10	Future.....	151-1

For online supplements and color versions of images, please go to [www.mhprofessional.com/
handbookofappliedhydrology](http://www.mhprofessional.com/handbookofappliedhydrology)

Contents

<i>Preface</i>	xxxv
<i>Foreword</i>	xxxix
<i>Acknowledgments</i>	xli
<i>Contributors</i>	xliii
<i>International Advisory Board</i>	liii
<i>Practitioner Advisory Board</i>	lv

Part 1. Fundamentals	1-1
Chapter 1. The Hydrologic Cycle.....	1-3
1.1 Characteristics of Water	1-3
1.2 Definition of Hydrology.....	1-4
1.3 Hydrologic Cycle	1-4
1.4 Components of the Hydrologic Cycle	1-5
1.5 Schematic Representation of the Hydrologic Cycle	1-5
1.6 Scales in Hydrologic Cycle	1-6
1.7 Impact of Climate Change on the Hydrologic Cycle	1-6
1.8 Influence of Human Activities and Land Use Changes on Hydrologic Cycle ...	1-6
1.9 Relation Between Hydrologic Cycle and Carbon and Nitrogen Cycles	1-7
1.10 Conclusion.....	1-9
References	1-9
Chapter 2. Watersheds, River Basins, and Land Use	2-1
2.1 Introduction	2-1
2.2 Components of Watersheds.....	2-1
2.3 Delineation of a Watershed	2-4
2.4 Watershed Hydrological Processes	2-4
2.5 Characteristics of a Watershed That Impact on Hydrological Processes.....	2-4
2.6 River Basin.....	2-6
2.7 River Basin Management	2-6
2.8 Major River Basins in the World	2-7
2.9 Land Use.....	2-7
2.10 Conclusion.....	2-8
References	2-8
Chapter 3. Water Balance	3-1
3.1 Introduction	3-1
3.2 Hydrologic Fluxes	3-1
3.3 Water on the Earth	3-1
3.4 Water Balance Modeling	3-4
3.5 Natural and Anthropogenic Effects on the Water Balance	3-7
3.6 Conclusion.....	3-9
References	3-9
PART 2. Data Collection and Processing.....	4-1
Chapter 4. Hydrometeors and Quantitative Precipitation Estimation	4-3
4.1 Introduction	4-3
4.2 Types of Hydrometeorological Data	4-3
4.3 Remote Sensing of Precipitation	4-3
4.4 Hydrometeorological Data Processing.....	4-4
4.5 Hydrometeorological Data Quality Assurance and Control	4-5
4.6 Quantitative Precipitation Estimate, Data Use, Archiving, and Accessibility ..	4-6

Chapter 5. Streamflow Data	5-1
5.1 Streamflow	5-1
5.2 Types of Streamflow Data	5-1
5.3 Streamgage Operation	5-1
5.4 Quality Assurance of Streamgage Data.....	5-6
5.5 Derived Streamflow Uncertainty.....	5-6
References	5-7
Chapter 6. Streamflow Ratings	6-1
6.1 Introduction.....	6-1
6.2 Rating Controls	6-1
6.3 Simple Ratings.....	6-4
6.4 Complex Ratings	6-6
6.5 Slope Ratings.....	6-8
6.6 Rate of Change of Stage Methods	6-8
6.7 Dynamic-Flow Model Methods.....	6-10
6.8 Index-Velocity Method	6-10
6.9 Shifting-Control Method for Dealing with Rating Complexities	6-11
6.10 Uncertainty in Ratings	6-13
References	6-13
Chapter 7. Hydrologic Information Systems.....	7-1
7.1 Introduction	7-1
7.2 Hydrologic Data Management	7-1
7.3 Service-Oriented Architectures for Integrating Distributed Hydrologic Data and Models	7-2
7.4 The CUAHSI Hydrologic Information System as an Example HIS	7-3
7.5 HydroShare as a Next-Generation HIS Software.....	7-5
7.6 Conclusion	7-8
References	7-8
Chapter 8. Remote Sensing Techniques and Data Assimilation for Hydrologic Modeling.....	8-1
8.1 Introduction	8-1
8.2 Remote Sensing Theory	8-1
8.3 Remote Sensing in Hydrological Sciences: A Historical Perspective.....	8-1
8.4 Remote Sensing: Methods and Techniques	8-2
8.5 Data Assimilation: Theory	8-3
8.6 Summary.....	8-4
References	8-4
Chapter 9. Geographic Information Systems	9-1
9.1 Introduction	9-1
9.2 Basic Principles of GIS	9-1
9.3 Data Sources and Characteristics.....	9-2
9.4 Representation of Model Inputs	9-5
9.5 Model/GIS Interfaces	9-7
9.6 Current Status and Future Directions.....	9-7
References	9-8
Chapter 10. Design of Hydrologic Networks.....	10-1
10.1 Introduction	10-1
10.2 Hydrologic Networks	10-1
10.3 Necessity of Hydrologic Networks	10-1
10.4 Impact of Hydrologic Network Density on Streamflow Estimates.....	10-2
10.5 Design Considerations.....	10-2
10.6 Design of Hydrologic Networks: Methodologies.....	10-2
10.7 Conclusion.....	10-4
References	10-4
Part 3. Methods	11-1
Chapter 11. Artificial Neural Networks	11-3
11.1 Introduction	11-3
11.2 Historical Development	11-3
11.3 Artificial Neural Networks	11-4
11.4 ANN Training and Testing.....	11-4

11.5 Drawbacks of ANN Technique	11-5
11.6 Shortcomings in ANN Modeling	11-5
11.7 Future Direction	11-6
References	11-6
Chapter 12. Fuzzy Logic.....	12-1
12.1 Fuzzy Logic Basics.....	12-1
12.2 Function of Fuzzy Numbers	12-2
12.3 Fuzzy Rule-Based Modeling (Fuzzy Inference).....	12-3
Acknowledgment	12-5
References	12-5
Chapter 13. Evolutionary Computing: Genetic Algorithms	13-1
13.1 Introduction	13-1
13.2 Evolutionary Computing in Hydrology: An Overview	13-1
13.3 Genetic Algorithms.....	13-2
13.4 GA Applications in Hydrology.....	13-3
13.5 Conclusion and Future Directions	13-3
References	13-3
Chapter 14. Relevance Vector Machine	14-1
14.1 Introduction	14-1
14.2 Background	14-1
14.3 Mathematical Formulation.....	14-2
14.4 Application of RVM.....	14-3
14.5 Examples from Hydrology and Future Scope.....	14-4
14.6 Miscellaneous Topics	14-5
References	14-6
Chapter 15. Harmonic Analysis and Wavelets.....	15-1
15.1 Introduction	15-1
15.2 The Continuous Wavelet Transform.....	15-1
15.3 Discrete Time Wavelet Transform and Multiresolution Analysis.....	15-3
15.4 Signal Energy Repartition in the Wavelet Frame.....	15-3
15.5 Wavelet Analysis of the Time-Scale Relationship Between Two Signals.....	15-4
15.6 Wavelet Cross Spectrum and Coherence	15-4
15.7 Applications of Wavelet Transforms in Hydrology and Earth Sciences.....	15-5
15.8 Perspectives	15-5
References	15-5
Chapter 16. Outlier Analysis and Infilling of Missing Records in Hydrologic Data.....	16-1
16.1 Introduction	16-1
16.2 Concepts and Methods for Outlier Analysis	16-2
16.3 Concepts and Methods for Handling Missing Records	16-3
16.4 Discussion and Concluding Remarks on Methods for Outliers and Infilling of Missing Records	16-5
16.5 Future Research Directions	16-6
References	16-6
Chapter 17. Linear and Nonlinear Regression	17-1
17.1 Linear and Nonlinear Regression	17-1
17.2 Measures for Goodness of Fit	17-4
17.3 Multiple Linear Regression	17-5
17.4 Nonlinear Regression.....	17-6
References	17-9
Chapter 18. Time Series Analysis and Models.....	18-1
18.1 Introduction	18-1
18.2 Properties of Hydrological Time Series	18-1
18.3 Time-Series Modeling	18-2
18.4 Modeling of Continuous Time Processes	18-2
18.5 Univariate Modeling	18-2
18.6 Univariate Periodic Modeling	18-4
18.7 Multivariate Modeling	18-6
18.8 Disaggregation Models.....	18-7
18.9 Nonparametric Models	18-7

18.10 Stochastic Simulation, Forecasting, and Uncertainty	18-8
18.11 Conceptual Stochastic Modeling	18-8
18.12 Final Remarks and Future Challenges	18-9
References	18-9
Chapter 19. Statistical Detection of Nonstationarity: Issues and Needs.....	19-1
19.1 Introduction	19-1
19.2 Exploratory Methods for Detection of Change	19-2
19.3 Statistical Exploration of Nonstationarity.....	19-2
19.4 Effect of Nonconstant Error Variation.....	19-3
19.5 Effect of <i>a Priori</i> Filtering of Time Series	19-4
19.6 Distribution of a Breakpoint	19-4
19.7 Conclusion.....	19-5
Chapter 20. Spatial Analysis and Geostatistical Methods.....	20-1
20.1 Introduction	20-1
20.2 Data Types and Methods	20-1
20.3 Spatial Analysis	20-1
20.4 Heterogeneous Field Estimation and Simulation	20-3
20.5 Summary.....	20-7
Acknowledgments	20-7
References	20-7
Chapter 21. Frequency Distributions	21-1
21.1 Introduction	21-1
21.2 Discrete Frequency Distributions.....	21-1
21.3 Classification of Continuous Frequency Distributions.....	21-2
21.4 Continuous Frequency Distributions	21-2
21.5 Conclusion.....	21-9
References	21-10
Chapter 22. Calibration, Parameter Estimation, Uncertainty, Data Assimilation, Sensitivity Analysis, and Validation.....	22-1
22.1 Introduction	22-1
22.2 Parameter Uncertainty	22-1
22.3 Parameter Estimation	22-3
22.4 Data Assimilation	22-5
22.5 Sensitivity Analysis.....	22-10
22.6 Validation Techniques	22-11
References	22-15
Chapter 23. Bayesian Methods	23-1
23.1 Introduction	23-1
23.2 The Bayesian Inference Framework.....	23-1
23.3 Computational Methods.....	23-4
23.4 Diagnostics to Scrutinize Model Assumptions.....	23-6
23.5 Applications in Hydrology	23-7
23.6 Conclusion.....	23-9
Acknowledgments	23-9
References	23-9
Chapter 24. Optimization Approaches for Integrated Water Resources Management.....	24-1
24.1 Introduction	24-1
24.2 Trends.....	24-2
24.3 Challenges and Research Gaps.....	24-4
24.4 Conclusion.....	24-5
24.5 Acknowledgments	24-5
24.6 Appendix: Literature Trend Analysis.....	24-5
References	24-5
Chapter 25. Nonparametric Methods	25-1
25.1 Introduction	25-1
25.2 Definitions.....	25-1
25.3 Methods.....	25-2
25.4 Applications	25-3
25.5 Discussion	25-4
References	25-5

Chapter 26. Predictive Uncertainty Assessment and Decision Making	26-1
26.1 Introduction	26-1
26.2 Forecasting in Hydrology	26-1
26.3 Motivations for Converting Deterministic to Stochastic Prediction	26-1
26.4 Predictive Uncertainty.....	26-2
26.5 Techniques Aimed at Assessing Predictive Uncertainty	26-4
26.6 Verification of the Estimated Predictive Density.....	26-9
26.7 Major Reasons Undermining the Operational Use of Predictive Uncertainty	26-9
26.8 Examples of Proper Use of Predictive Uncertainty to Improve Decisions	26-13
References	26-15
Chapter 27. Risk-Reliability Analysis.....	27-1
27.1 Introduction	27-1
27.2 Measures of Reliability	27-1
27.3 Performance Function and Reliability Index	27-2
27.4 Direct Integration Method	27-2
27.5 First-Order Second-Moment Reliability Methods.....	27-3
27.6 Time-Dependent (Dynamic) Reliability Models	27-5
27.7 Time-to-Failure Analysis	27-5
27.8 Monte Carlo Simulation	27-6
References	27-9
Chapter 28. Scaling and Fractals	28-1
28.1 Introduction	28-1
28.2 Scale-Invariant Sets and Functions	28-1
28.3 Some Properties of <i>H</i> - <i>SSS</i> / Processes and <i>MF</i> Cascades	28-2
28.4 Inference of Scaling for Stationary Multifractal Measures.....	28-4
28.5 Processes with Limited Scale Invariance	28-4
28.6 Conclusion.....	28-5
Acknowledgments	28-5
References	28-5
Chapter 29. Nonlinear Dynamics and Chaos.....	29-1
29.1 Introduction	29-1
29.2 Chaos Theory: A Brief History	29-2
29.3 Chaos Concepts and Identification Methods	29-2
29.4 Issues in Chaos Identification and Prediction	29-5
29.5 Hydrologic Applications	29-7
29.6 Final Remarks.....	29-7
Acknowledgments	29-8
References	29-8
Chapter 30. Copula Modeling in Hydrologic Frequency Analysis...	30-1
30.1 Introduction	30-1
30.2 Description of Copula Models.....	30-1
30.3 Overview of Model Selection	30-2
30.4 Multivariate Quantile and Return Period.....	30-5
30.5 An Illustration: The Fraser River at Hope	30-5
30.6 Extensions.....	30-7
30.7 Resources and Further Specific References.....	30-8
Acknowledgments	30-9
References	30-9
Chapter 31. Entropy Theory.....	31-1
31.1 Origin	31-1
31.2 Definition	31-1
31.3 Forms of Entropy	31-2
31.4 Directional Information Transfer Index	31-3
31.5 Entropy under Transformation of Variables	31-3
31.6 Informational Correlation Coefficient.....	31-3
31.7 Total Correlation	31-3
31.8 Theory of Entropy	31-4
31.9 Methodology for Application	31-4
31.10 Hydrologic Modeling Using Entropy Theory	31-7
31.11 Conclusion	31-8
References	31-8

Chapter 32. Entropy Production Extremum Principles	32-1
32.1 Introduction	32-1
32.2 Background and Review	32-1
32.3 Maximum Entropy Analysis	32-4
32.4 Review of Applications in Hydrology and Hydraulics	32-5
32.5 Conclusion.....	32-5
References	32-5
Chapter 33. Data-Based Mechanistic Modeling	33-1
33.1 Introduction	33-1
33.2 The Main Stages of DBM Modeling	33-2
33.3 Linear DBM Models	33-3
33.4 Time Variable and State-Dependent Parameter Models.....	33-6
33.5 Hypothetico-Inductive DBM Modeling.....	33-7
33.6 DBM Emulation Modeling of High-Order Simulation Models.....	33-8
33.7 Conclusion.....	33-11
References	33-11
Chapter 34. Decomposition Methods	34-1
34.1 Introduction: Adomian's Decompositions Method.....	34-1
34.2 Regional Flow in an Unconfined Aquifer	34-2
34.3 Propagation of Nonlinear Kinematic Flood Waves in Rivers	34-2
34.4 Nonlinear Infiltration in Unsaturated Soils	34-4
34.5 Summary and Conclusion.....	34-4
References	34-5
Chapter 35. Network Theory	35-1
35.1 Introduction	35-1
35.2 Network Theory: Concept and History	35-2
35.3 Network Types	35-3
35.4 Network Measures	35-4
35.5 Applications in Hydrology	35-6
35.6 Conclusion.....	35-8
Acknowledgments	35-8
References	35-8
Chapter 36. Hydroeconomic Analysis	36-1
36.1 Introduction	36-1
36.2 Estimating the Economic Value of Water	36-1
36.3 Water Demand Functions	36-2
36.4 Considerations in the Design of Hydroeconomic Analysis Studies	36-3
36.5 Applications and Implementation of Hydroeconomic Analysis for Management and Decision Support	36-5
36.6 Discussion of Challenges, Limitations, and Future Directions	36-6
36.7 Conclusion.....	36-7
References	36-7
Part 4. Hydrologic Processes and Modeling	37-1
Chapter 37. Weather and Climate.....	37-3
37.1 Introduction	37-3
37.2 Hydrologic Engineering and Intersection with Weather and Climate	37-3
37.3 Weather	37-5
37.4 Observing Weather.....	37-7
37.5 Climate	37-7
37.6 Climate Change	37-8
References	37-10
Chapter 38. Hydroclimatology: Global Warming and Climate Change	38-1
38.1 Introduction: The Ambiguity of Climate	38-1
38.2 Natural and Human Influences on Present-Day Climate	38-1
38.3 Impacts of Climate Change on the Hydrological Cycle in the Twentieth and Twenty-First Centuries.....	38-2
38.4 Global Climate Models	38-3
38.5 Working with Climate Model Projections	38-4
38.6 Conclusion.....	38-6
References	38-6

Chapter 39. Spatial and Temporal Estimation and Analysis of Precipitation	39-1
39.1 Introduction	39-1
39.2 Estimates of Mean Areal Precipitation	39-1
39.3 Missing Precipitation Data Estimation Methods.....	39-4
39.4 Limitations of Estimation Methods	39-5
39.5 New Methods for Missing Data Estimation	39-5
39.6 Summary of Issues for Missing Precipitation Data Estimation	39-6
39.7 Conclusion.....	39-7
References	39-8
Chapter 40. Snow Distribution and Snowpack Characteristics	40-1
40.1 Introduction	40-1
40.2 Processes Controlling Snow Distribution	40-1
40.3 Spatial Patterns of Snow at Various Scales	40-2
40.4 Snowpack Characteristics	40-2
40.5 Discussion and Conclusion.....	40-3
Acknowledgment.....	40-4
References	40-4
Chapter 41. Time-Space Modeling of Precipitation	41-1
41.1 Introduction	41-1
41.2 Stochastic Modeling of Precipitation	41-1
41.3 Deterministic Numerical Modeling of Time-Space Precipitation	41-3
41.4 Remote Sensing for the Modeling of Time-Space Precipitation.....	41-7
References	41-10
Chapter 42. Evapotranspiration and Evaporative Demand	42-1
42.1 Introduction and History of Theory.....	42-1
42.2 Relevant Concepts and Methods	42-3
42.3 Outstanding Problems and Directions for Future Work	42-10
Acknowledgments	42-14
References	42-14
Chapter 43. Rainfall Interception, Detention, and Depression Storage.....	43-1
43.1 Canopy Interception Loss.....	43-1
43.2 Forest Floor Interception Loss.....	43-3
43.3 Detention and Depression Storage	43-3
43.4 Summary	43-3
References	43-3
Chapter 44. Watershed Geomorphological Characteristics	44-1
44.1 Introduction and Literature Review	44-1
44.2 Watersheds and Drainage Networks.....	44-2
44.3 Outstanding Problems and Directions for Future Work	44-10
References	44-11
Chapter 45. Infiltration Modeling.....	45-1
45.1 Introduction	45-1
45.2 Basic Equations for Vertical Infiltration	45-1
45.3 Classical Models for Point Infiltration into Vertically Homogeneous Soils ...	45-2
45.4 Modeling of Point Infiltration into Vertically Nonuniform Soils.....	45-4
45.5 Models for Rainfall Infiltration over Heterogeneous Areas	45-5
45.6 Soil Conservation Service Runoff Curve Number Model.....	45-6
45.7 Open Problems	45-6
References	45-7
Chapter 46. Soil Moisture and Vadose Zone Modeling	46-1
46.1 Background	46-1
46.2 Continuum-Scale Models for Partially Saturated Flow in the Vadose Zone ..	46-2
46.3 Numerical Vadose Zone and Land Surface Models.....	46-3
46.4 Soil Moisture across Spatial-Temporal Scales.....	46-5
46.5 Inverse Modeling—Soil Hydraulic Properties at the Model Grid Scale ..	46-8
46.6 Summary	46-10
References	46-11

Chapter 47. Hydrogeologic Characterization	47-1
47.1 Introduction	47-1
47.2 Borehole Samples and Groundwater Monitoring Wells	47-1
47.3 Investigation of Borehole Drilling	47-1
47.4 Cone Penetrometry, Permeametry, and Electrical Conductivity Logging	47-2
47.5 Electrical Resistivity Survey	47-2
47.6 Hydraulic Methods for in Situ Conductivity Measurement	47-2
47.7 Characterization of the Hydraulic Gradient and Flow Rates	47-3
47.8 Recharge Estimation	47-3
47.9 Summary	47-3
References	47-3
Chapter 48. Groundwater Modeling	48-1
48.1 Introduction	48-1
48.2 Groundwater Model Development	48-1
48.3 Grid Generation	48-2
48.4 Model Calibration	48-3
48.5 Case Study: Groundwater Modeling in Baton Rouge, Southeastern Louisiana	48-3
48.6 Summary	48-5
Acknowledgments	48-7
References	48-7
Chapter 49. Watershed Runoff, Streamflow Generation, and Hydrologic Flow Regimes	49-1
49.1 Introduction	49-1
49.2 Dominant Runoff Generation Mechanisms	49-3
49.3 Infiltration Equations	49-6
49.4 Factors Affecting Runoff	49-6
49.5 Poorly Understood Factors Affecting Runoff Generation	49-7
Acknowledgments	49-11
References	49-11
Chapter 50. Snowmelt Runoff Generation and Modeling	50-1
50.1 Introduction	50-1
50.2 Snow Accumulation Processes	50-1
50.3 Energy Budget of Snow Pack and Snowmelt	50-2
50.4 Simulation of Snow Accumulation Processes	50-3
50.5 Heat and Water Transfer in Melting Snow Cover	50-3
50.6 Spatial Variability of Snow Cover	50-4
50.7 Constructing General Model of Snowmelt Runoff Generation	50-4
50.8 Case studies	50-6
References	50-9
Chapter 51. Glacial Melting and Runoff Modeling	51-1
51.1 Introduction	51-1
51.2 Remote Sensing	51-1
51.3 Application of Remote Sensing in Glacier Quantification	51-1
51.4 Glaciated Versus Nonglaciated Watersheds	51-3
51.5 Application in Streamflow Measurement	51-3
51.6 Conclusion	51-4
References	51-4
Chapter 52. Reservoir and Channel Routing	52-1
52.1 Introduction	52-1
52.2 Reservoir Routing	52-1
52.3 River Routing	52-2
52.4 The Classical Muskingum Flood Routing Method	52-3
52.5 Nash Cascade Model for River Routing	52-4
52.6 Other Linear Storage Models	52-4
52.7 Linear Diffusion Analogy Routing Method	52-5
52.8 Nonlinear Routing Methods	52-5
52.9 Flow Routing Using Hydraulic Methods	52-6
52.10 Basis for the Development of Simplified Momentum Equations	52-7
52.11 Simplified Hydraulic Flood Routing Methods	52-7
52.12 Kalinin–Milyukov Method	52-9
52.13 Variable Parameter Muskingum Stage Routing Method	52-12

52.14 Conclusion	52-14
Acknowledgment	52-14
References	52-15
Chapter 53. Waterlogging and Salinization	53-1
53.1 Introduction	53-1
53.2 Salinity Features and Impacts	53-1
53.3 Irrigation Induced Rises of the Watertable	53-2
53.4 Irrigation Induced Land Salinization	53-3
53.5 Land Salinization Control	53-4
53.6 Salt Balance and Leaching Calculations	53-4
53.7 Monitoring and Mapping	53-5
53.8 Remedial Measures	53-5
53.9 New Challenges	53-6
53.10 Conclusion	53-6
References	53-7
Chapter 54. Surface Water–Groundwater Interactions: Integrated Modeling of a Coupled System.....	54-1
54.1 Introduction	54-1
54.2 Surface Water Models	54-2
54.3 Subsurface Models	54-4
54.4 Soil Plant Models	54-5
54.5 Coupling Methods	54-6
54.6 Scale Issues	54-7
54.7 Data Requirements	54-9
54.8 Integrated Models and Watershed Applications	54-10
54.9 Conclusion	54-10
References	54-12
Chapter 55. Seawater Intrusion in Coastal Aquifers: Concepts, Mitigation, and Simulation	55-1
55.1 Introduction	55-1
55.2 Assumptions and Approaches for Modeling Seawater Intrusion	55-1
55.3 Mitigation of Seawater Intrusion	55-3
55.4 Case Study: The Nile Delta Aquifer	55-3
55.5 Conclusion	55-9
References	55-9
Chapter 56. Regional Land Subsidence Caused by the Compaction of Susceptible Aquifer Systems Accompanying Groundwater Extraction	56-1
56.1 Introduction	56-1
56.2 Detection and Assessment	56-2
56.3 Analysis and Simulation	56-7
Acknowledgments	56-9
References	56-9
Chapter 57. Hydraulic Fracturing and Hydrologic Impacts	57-1
57.1 Introduction	57-1
57.2 Hydraulic Fracturing Process	57-2
57.3 Risk of Groundwater Contamination	57-4
57.4 Potential for Induced Seismicity	57-6
57.5 Conclusion	57-7
References	57-8
Chapter 58. Catchment Classification and Regionalization	58-1
58.1 Introduction	58-1
58.2 Catchment Classification: A Review	58-2
58.3 Classification Based on Chaos Theory	58-2
58.4 Classification Based on Network Theory	58-4
58.5 Conclusion	58-5
Acknowledgments	58-7
References	58-7

Chapter 59. Rainfall-Runoff Modeling	59-1
59.1 Introduction	59-1
59.2 A Brief History	59-1
59.3 Computation of Runoff Volume	59-1
59.4 Determination of Peak Discharge	59-3
59.5 Runoff Hydrograph	59-3
59.6 Computation of Runoff Hydrograph by Hydraulic Approaches	59-6
59.7 Conclusion.....	59-8
References	59-8
Chapter 60. Continuous Watershed Modeling	60-1
60.1 Introduction	60-1
60.2 Historical Development	60-2
60.3 Concepts and Methods	60-3
60.4 Outstanding Problems/Needs.....	60-7
60.5 Future Directions	60-8
References	60-10
Chapter 61. Calibration and Evaluation of Watershed Models	61-1
61.1 Introduction	61-1
61.2 Calibration and Evaluation	61-2
61.3 Elements of a Calibration/Evaluation Strategy	61-2
61.4 Historical Perspective	61-2
61.5 Model Calibration and Evaluation Protocol	61-3
61.6 Strategies for Calibration	61-3
61.7 Desirable Properties of a Successful Calibration.....	61-4
61.8 Preparation Phase.....	61-4
61.9 Calibration Phase	61-8
61.10 Evaluation Phase.....	61-8
61.11 Discussion and Conclusion	61-9
References	61-9
Chapter 62. Feasibility, Engineering, and Operations Models: Using the Decision Environment to Inform the Model Design	62-1
62.1 Introduction	62-1
62.2 The Decision Environment	62-1
62.3 USACE Decision Environment Schemes	62-2
62.4 Precision Dimensions of Decision Support.....	62-2
62.5 Process Representation.....	62-3
62.6 Information Content Scale.....	62-5
62.7 Case Study: Picayune Strand-Restoration Project.....	62-5
62.8 Future Research.....	62-6
62.9 Summary	62-6
References	62-7
Part 5. Sediment and Pollutant Transport	63-1
Chapter 63. Water Quality	63-3
63.1 Introduction	63-3
63.2 Water Pollution	63-3
63.3 Water Quality Standards and Water Use Designations	63-3
63.4 Restoration of Water Quality.....	63-5
63.5 Sensor-Based Water Quality Monitoring Technologies.....	63-8
References	63-9
Chapter 64. Soil Erosion	64-1
64.1 Introduction	64-1
64.2 Erosion by Wind.....	64-1
64.3 Erosion by Water	64-1
64.4 Gravity-Induced Erosion.....	64-2
64.5 Tillage Erosion	64-3
64.6 Snowmelt Erosion	64-3
64.7 Irrigation-Induced Erosion.....	64-3
64.8 Erosion by Wind-Driven Rain.....	64-3
64.9 Erosion Assessment	64-4
64.10 Erosion Assessment—Field and Laboratory Measurements	64-4

64.11 Erosion Assessment—Equations and Models	64-5
64.12 Erosion Impacts.....	64-5
64.13 Erosion Control and Soil Conservation	64-5
64.14 Conclusion	64-6
References	64-6
Chapter 65. Channel Erosion and Sediment Transport	65-1
65.1 Introduction	65-1
65.2 Sediment Production and Loads	65-1
65.3 Partitioning of Sediment Loads in Channels	65-2
65.4 Bank Profile and Erosional Modes.....	65-3
65.5 Modes of Sediment Transport.....	65-5
65.6 Conclusion.....	65-10
References	65-10
Chapter 66. Sedimentation of Floodplains, Lakes, and Reservoirs.....	66-1
66.1 Floodplain	66-1
66.2 Lake	66-1
66.3 Reservoir	66-2
66.4 The Sedimentation Process	66-5
66.5 Prediction of Sediments in Floodplains.....	66-7
66.6 Reservoir Trap Efficiency	66-7
66.7 Estimation of Sediment in Lakes and Reservoirs.....	66-7
66.8 Protective Measure Against Sedimentation	66-9
66.9 Summary	66-9
Acknowledgment.....	66-10
References	66-10
Chapter 67. Pollutant Transport in Surface Water.....	67-1
67.1 Introduction	67-1
67.2 Fundamental Processes Controlling Pollutant Transport.....	67-1
67.3 Pollutant Transport in Rivers and Streams	67-3
67.4 Pollutant Transport in Lakes and Reservoirs	67-4
67.5 Pollutant Transport in Coastal Waters	67-7
References	67-9
Chapter 68. Pollutant Transport in Vadose Zone.....	68-1
68.1 Introduction	68-1
68.2 Water Potential in the Unsaturated Zone	68-1
68.3 Governing Equation of Flow in Vadose Zone	68-1
68.4 Deterministic Approach to Solute Transport in the Vadose Zone	68-3
68.5 Codes for Numerical Solution of Vadose Zone Flow and Transport.....	68-5
References	68-6
Chapter 69. Pollutant Transport in Groundwater	69-1
69.1 Introduction	69-1
69.2 Learn from the Field Work—A Case of Saltwater Intrusion Observation	69-3
69.3 Reactive Solute Transport Modeling	69-3
69.4 Dispersion Processes in Groundwater (Sato and Lwasa, 2003)	69-5
69.5 Conclusion.....	69-9
References	69-9
Chapter 70. Salinization and Salinity Management in Watersheds....	70-1
70.1 Introduction.....	70-1
70.2 Salinization.....	70-1
70.3 Salinity-Related Concerns	70-2
70.4 Salinity Management.....	70-2
70.5 Salinity Modeling	70-3
Acknowledgments	70-4
References	70-4
Chapter 71. Transport of Biochemicals and Microorganisms.....	71-1
71.1 Introduction	71-1
71.2 Biochemicals and Microorganisms	71-1

71.3 Mathematical Model Development.....	71-2
71.4 Conclusion.....	71-6
Acknowledgments	71-6
References	71-6
Part 6. Hydrometeorologic and Hydrologic Extremes	72-1
Chapter 72. Atmospheric Rivers	72-3
72.1 Introduction	72-3
72.2 Large-Scale Circulation and Moisture Sources and Pathways.....	72-4
72.3 Precipitation and Flooding Associated with ARs.....	72-4
72.4 Modeling of ARs and Associated Precipitation	72-5
72.5 Projection of Future Changes in ARs.....	72-6
72.6 Future Challenges.....	72-7
Acknowledgments	72-8
References	72-8
Chapter 73. Hydrometeorological Extremes (Hurricanes and Typhoons).....	73-1
73.1 Introduction	73-1
73.2 Climatology of Heavy Rainfall and Flooding from Tropical Cyclones	73-1
73.3 Remote Rainfall Associated with Tropical Cyclones: Predecessor Rain Events	73-2
73.4 Projected Increases in Rainfall Associated with Tropical Cyclones	73-2
References	73-3
Chapter 74. Extreme Rainfall: Global Perspective.....	74-1
74.1 Introduction: The Importance of Studying Extreme Rainfall and Related Difficulties	74-1
74.2 A Global Survey of Record Rainfall Depths	74-3
74.3 Approaches in Estimating Extreme Rainfall	74-7
74.4 The Concept of Probable Maximum Precipitation	74-10
74.5 Probabilistic Approach to Extreme Rainfall	74-12
74.6 Ombrion (Intensity-Duration-Frequency) Curves	74-13
74.7 Summary and Conclusion.....	74-15
Acknowledgments	74-15
References	74-16
Chapter 75. Floods	75-1
75.1 Introduction to Floods and Flooding	75-1
75.2 Flood Characteristics	75-1
75.3 Flood Processes	75-2
75.4 Estimation of Flood Magnitudes and Design Floods	75-4
References	75-5
Chapter 76. Flood Frequency Analysis	76-1
76.1 Introduction	76-1
76.2 Describing the Chance of Flood	76-1
76.3 Looking at the Data	76-3
76.4 Fitting Distributions.....	76-4
76.5 Index Flood Method.....	76-5
76.6 Method of Moments, Bulletin 17B, and Bulletin 17C, with the LP3 Distribution	76-6
76.7 Uncertainty Analysis	76-6
76.8 Estimation at Ungaged Sites	76-7
76.9 Conclusion.....	76-7
References	76-7
Chapter 77. Regional Flood Frequency Modeling.....	77-1
77.1 Introduction: The Regional Framework	77-1
77.2 Regional Estimation Procedures	77-1
77.3 Delineation of Homogeneous Regions and Homogeneity Testing	77-1
77.4 Regional Transfer Methods	77-3
77.5 One-Step Regional Methods	77-4
77.6 Nonlinear Models in Regional Flood Frequency Modeling	77-4
77.7 Multivariate Regional Flood Frequency Modeling	77-5

77.8 Nonstationary Regional Flood Frequency Approaches.....	77-5
77.9 Regional Flood Frequency Analysis Based on Seasonality Measures	77-6
77.10 Combination of Local and Regional Approaches	77-6
77.11 Daily Streamflow Estimation at Ungauged Sites.....	77-6
77.12 Discussion and New Directions	77-7
References	77-7
Chapter 78. Risk, Reliability, and Return Periods and Hydrologic Design	78-1
78.1 Introduction	78-1
78.2 Probabilistic- and Risk-Based Approaches to Hydrologic Design	78-2
78.3 Multivariate Probabilistic- and Risk-Based Approaches to Hydrologic Design	78-7
References	78-9
Chapter 79. Drought Characteristics	79-1
79.1 Introduction	79-1
79.2 Drought, Aridity, and Water Scarcity.....	79-2
79.3 Drought Occurrences in the World.....	79-3
79.4 Drought Properties Based on Statistical Techniques	79-3
79.5 Numerical Characterization of Drought Properties	79-4
79.6 Indices for Drought Characterization	79-6
79.7 Outstanding Problems and Direction for Future Work	79-8
Acknowledgments	79-10
References	79-10
Chapter 80. Low Flow and Drought Analysis	80-1
80.1 Introduction	80-1
80.2 Need for Low Flow Hydrology Research	80-1
80.3 Factors Affecting Low Flows	80-2
80.4 Low Flow Indices.....	80-2
80.5 Methods of Low Flow Estimation in Ungaged Catchments	80-4
80.6 Drought Analysis.....	80-4
80.7 Conclusion.....	80-9
References	80-9
Part 7. Systems Hydrology	81-1
Chapter 81. Isotope Hydrology	81-3
81.1 Introduction.....	81-3
81.2 Isotopes	81-3
81.3 Groundwater Dating	81-5
81.4 Sampling Methods and Isotope Measurements	81-7
81.5 Isotope Applications in Hydrology	81-8
References	81-12
Chapter 82. Lake Hydrology	82-1
82.1 Introduction	82-1
82.2 Origin of Lakes.....	82-1
82.3 Water Balance of Lakes	82-1
82.4 Thermal Regime of Lakes	82-2
82.5 Ice Growth on Lakes.....	82-4
82.6 Circulation Processes in Lakes.....	82-4
References	82-5
Chapter 83. Urban Hydrology	83-1
83.1 Introduction	83-1
83.2 The Effects of Urbanization	83-2
83.3 Other Aspects of Urban Hydrology	83-3
83.4 Conclusion.....	83-3
References	83-4
Chapter 84. Agricultural Hydrology.....	84-1
84.1 Introduction	84-1
84.2 Water Movement in the Root Zone	84-1
84.3 Evaporation and Transpiration	84-3
References	84-4

Chapter 85. Forest Hydrology	85-1
85.1 Introduction	85-1
85.2 Historical Development	85-1
85.3 Principles of Forest Hydrology	85-2
85.4 Research Methods	85-3
85.5 Key Findings in Forest-Stream Water Quantity and Quality Relationships...	85-4
85.6 Future Directions	85-5
References	85-5
Chapter 86. Coastal Hydrology	86-1
86.1 Introduction	86-1
86.2 Overview of Coastal Processes	86-1
86.3 Movement of Water and Sediment in Coastal Areas	86-2
86.4 Mathematical Models of Water and Sediment Movement	86-6
86.5 Summary and Outlook	86-7
Acknowledgments	86-8
References	86-8
Chapter 87. Wetland Hydrology	87-1
87.1 Introduction	87-1
87.2 Importance of Hydrology on Wetland Functioning	87-1
87.3 Hydroperiod	87-2
87.4 Wetland Hydrologic Terms	87-2
87.5 Wetland Water Budget	87-3
87.6 Wetland Hydraulics	87-5
87.7 Modeling Groundwater-Surface Water Interactions	87-6
87.8 Wetland Hydrology at the Watershed Scale	87-7
87.9 Anthropogenic and Climate Change Impacts on Wetlands	87-7
87.10 Summary	87-7
References	87-8
Chapter 88. Arid Zone Hydrology	88-1
88.1 Introduction	88-1
88.2 Precipitation	88-1
88.3 Condensation	88-1
88.4 Infiltration	88-1
88.5 Runoff	88-2
88.6 Transmission Losses	88-3
88.7 Change in Storage (ΔS)-Groundwater Recharge	88-3
88.8 Evapotranspiration	88-4
88.9 Conclusion	88-6
References	88-6
Chapter 89. Karst	89-1
89.1 Introduction	89-1
89.2 Investigation and Characterization of Karst	89-4
89.3 Summary	89-10
Acknowledgments	89-11
References	89-11
Chapter 90. Cryospheric Hydrology: Mountainous Environment...	90-1
90.1 Introduction	90-1
90.2 Alpine Runoff	90-1
90.3 Monsoon Dominated Asian Mountain Ranges	90-1
90.4 Glacier Runoff as a Resource	90-1
90.5 Glacier Melting Processes	90-4
90.6 Glacier Melt Modeling	90-5
90.7 Drainage and Storage Characteristics	90-5
90.8 Diurnal and Seasonal Variations in Glacier Meltwater	90-6
90.9 Cryospheric Hydrology and Climate Change	90-7
90.10 Glacier Lake Outburst Floods	90-9
90.11 Summary	90-10
References	90-10

Chapter 91. Hydrology of Transportation Systems	91-1
91.1 Pathways in Nature.....	91-1
91.2 Scales of Movement and Accumulation Processes	91-2
91.3 Soil and Groundwater	91-3
91.4 Streams	91-4
91.5 Lakes.....	91-5
References	91-6
Chapter 92. Large-Scale and Global Hydrology.....	92-1
92.1 Introduction	92-1
92.2 The Distribution of Water on Earth	92-1
92.3 The Global Water Cycle	92-1
92.4 Numerical Modeling and Data Assimilation	92-2
92.5 Global Water Cycle Variability, Predictability, and Change	92-4
Acknowledgments	92-5
References	92-6
Part 8. Hydrology of Large River and Lake Basins	93-1
Chapter 93. Amazon River Basin.....	93-3
93.1 Main Geographical Features	93-3
93.2 Amazon Hydrological Processes.....	93-3
93.3 Environment, Economics and Potentialities of the Basin	93-5
93.4 Impact of <i>Anthropic Activities</i> in the Basin	93-6
93.5 Amazon Basin in the Context of Its Water Footprint and Environmental Role	93-6
References	93-6
Chapter 94. Paraná (Rio de la Plata) River Basin	94-1
94.1 Introduction.....	94-1
94.2 Geographical Features and Main Regions	94-1
94.3 Climate.....	94-1
94.4 Hydrological Features and Water Use.....	94-2
94.5 Variability and Trends	94-2
References	94-4
Chapter 95. Orinoco River Basin.....	95-1
95.1 Introduction	95-1
95.2 Regional Geological and Topographical Setting.....	95-1
95.3 Hydroclimatic Conditions.....	95-1
95.4 The Main Stem and Its Major Tributaries	95-2
95.5 Floodplains and Seasonal Sediment Regime	95-2
95.6 Delta	95-3
95.7 Regional Vegetation	95-4
95.8 Human Impacts	95-4
95.9 Conclusion.....	95-4
References	95-4
Chapter 96. Nile River Basin.....	96-1
96.1 Introduction	96-1
96.2 Climate.....	96-3
96.3 Hydrology of the Nile Basin	96-4
References	96-9
Chapter 97. Congo River Basin	97-1
97.1 Introduction	97-1
97.2 The State of Hydrological Monitoring	97-1
97.3 Climate Regimes	97-2
97.4 Catchments Characteristics and Hydrological Similarities	97-2
97.5 Hydrogeochemical Processes and Sediment Transport	97-4
97.6 Hydrological Modeling	97-4
97.7 Climate and Land Use Change	97-5
97.8 Conclusion.....	97-5
Acknowledgment	97-5
References	97-5

Chapter 98. Zambezi River Basin.....	98-1
98.1 Introduction	98-1
98.2 Physical Characterization.....	98-1
98.3 Main Features.....	98-1
98.4 Climate.....	98-3
98.5 Runoff Regime.....	98-3
98.6 Past Hydrological Studies.....	98-4
98.7 Hydrological Data.....	98-5
98.8 Current Concerns and Future Challenges	98-6
Acknowledgments	98-6
References	98-6
Chapter 99. Euphrates and Tigris River Basin.....	99-1
99.1 General Characteristics of the Basin	99-1
99.2 Hydrology and Water Resources.....	99-1
99.3 Water Resources Developments in the Basin	99-3
99.4 Environmental Concerns.....	99-3
99.5 Climate Change Impacts on Basin Hydrology	99-3
Acknowledgment	99-3
References	99-4
Chapter 100. Yangtze River Basin.....	100-1
100.1 Introduction.....	100-1
100.2 Climate and Hydrology.....	100-2
100.3 Station Network and Water Conservancy Projects.....	100-4
100.4 Significant Water Issues	100-5
100.5 Research on the Yangtze River Basin	100-5
100.6 Conclusion	100-5
References	100-6
Chapter 101. Yellow River Basin	101-1
101.1 Introduction.....	101-1
101.2 Climate and Hydrology.....	101-3
101.3 Station Network and Water Conservancy Projects.....	101-4
101.4 Significant Water Issues	101-5
101.5 Research on the Yellow River basin.....	101-5
101.6 Conclusion	101-6
References	101-6
Chapter 102. Mekong River	102-1
102.1 Introduction.....	102-1
102.2 Upper Mekong River (Langcang Jiang)	102-3
102.3 Lower Mekong River	102-5
102.4 Floods and Flood Forecasting.....	102-6
102.5 Mekong Delta	102-8
102.6 Biodiversity	102-8
102.7 Agriculture and Aquaculture.....	102-8
102.8 Mekong River Commission	102-9
102.9 Environmental Threats	102-9
102.10 Conclusion	102-9
References	102-9
Chapter 103. Yenisei River Basin.....	103-1
103.1 Introduction.....	103-1
103.2 Central and Lower Sections of the Yenisei.....	103-1
103.3 Upper Section of the Yenisei	103-1
103.4 Fluvial System of the Angara River	103-1
References	103-4
Chapter 104. Lena River Basin.....	104-1
104.1 Introduction.....	104-1
References	104-4
Chapter 105. Brahmaputra River Basin	105-1
105.1 Introduction	105-1
105.2 Climate	105-1

105.3 Drainage Characteristics	105-2
105.4 Hydrology.....	105-4
105.5 Problems Faced, Projects Undertaken, and Future Scope	105-5
References	105-6
Chapter 106. Ganga River Basin	106-1
106.1 Ganga River Basin	106-1
106.2 Ganga River	106-1
106.3 Climate and Hydrology of the Ganga Basin	106-2
106.4 Floods and Droughts.....	106-2
106.5 Groundwater Resources	106-2
106.6 Hydropower	106-2
106.7 Sediments.....	106-3
106.8 Water Quality Aspects.....	106-3
106.9 Major Water Resources Development Projects	106-3
106.10 Social and Environmental Aspects	106-3
106.11 Future Perspectives.....	106-4
References	106-4
Chapter 107. Narmada Basin.....	107-1
107.1 Introduction	107-1
107.2 Population	107-2
107.3 Major Tributaries and Sub-Basins	107-2
107.4 Climate in Narmada Basin	107-3
107.5 Soils and Land Use in Narmada Basin	107-4
107.6 Water Resources of Narmada Basin.....	107-4
107.7 Major Water Resources Projects in Narmada Basin	107-5
107.8 Conclusion	107-6
References	107-6
Chapter 108. Indus River Basin	108-1
108.1 Introduction to Indus River Basin	108-1
108.2 Physiography of Indus River Basin	108-1
108.3 River Network and Principal Hydrologic Units of Indus River Basin	108-1
108.4 Climate of Indus River Basin	108-2
108.5 Hydrological Characteristics of Indus River Basin	108-3
108.6 Indus Water Treaty	108-5
108.7 Major Water Resources Development Projects in Indus River Basin.....	108-5
108.8 Groundwater Resources of Indus River Basin	108-9
108.9 Climate Change in Indus River Basin and Its Hydrologic Consequences....	108-9
108.10 Conclusion	108-10
References	108-10
Chapter 109. The Mississippi River Basin.....	109-1
109.1 Mississippi River Basin Physiography and Hydrology.....	109-1
109.2 Mississippi River Basin Climatology	109-1
109.3 Anthropogenic Changes in the River Basin	109-2
109.4 Future Critical Challenges in the Mississippi River Basin	109-4
Acknowledgments	109-4
References	109-5
Chapter 110. Colorado River Basin	110-1
110.1 Introduction and Basin Characteristics	110-1
110.2 History of Water Resources Allocation.....	110-1
110.3 Reservoirs and Other Water Management Facilities	110-2
110.4 Development and Use of the Colorado River Simulation System	110-3
110.5 Hydrologic Data	110-3
110.6 Generating Projected Future Flow Scenarios	110-4
110.7 Future Priorities	110-4
References	110-4
Chapter 111. Columbia River Basin	111-1
111.1 Introduction.....	111-1
111.2 Basin History	111-1
111.3 River Operations	111-2

111.4 Current and Future Concerns	111-4
111.5 Future Opportunities and Challenges	111-5
Acknowledgments	111-5
References	111-5
Chapter 112. St. Lawrence River Basin	112-1
112.1 Introduction.....	112-1
112.2 Characteristics of the St. Lawrence River and Its Basin.....	112-1
112.3 Hydrological Characteristics of the River	112-4
Acknowledgments	112-5
References	112-5
Chapter 113. River Rhine Basin.....	113-1
113.1 Introduction.....	113-1
113.2 Climate.....	113-1
113.3 Water Balance in the Rhine Basin.....	113-4
113.4 Long-Term Variability of Hydrometeorological Variables in the Rhine Basin	113-4
113.5 Discharge Characteristics in Longitudinal Profile.....	113-5
113.6 The Runoff Regime of the Rhine.....	113-6
113.7 Changes in the Runoff Characteristics of the Rhine Since the Beginning of the Twentieth Century	113-9
113.8 Changes in the Runoff Regime of the Upper Rhine	113-10
113.9 Changes in the Runoff Regime of the Middle and Lower Rhine	113-10
113.10 Development in Extreme Runoff Situations: Flood	113-10
113.11 Development in Extreme Runoff Situations: Low Water.....	113-10
Acknowledgment	113-10
References	113-10
Chapter 114. Danube River Basin.....	114-1
114.1 Introduction.....	114-1
114.2 History of the River System	114-1
114.3 Climate, Drainage Characteristics, and Hydrology.....	114-2
114.4 Problem Faced	114-3
114.5 Scope of Future Development	114-5
References	114-5
Chapter 115. Ob River Basin	115-1
115.1 Introduction.....	115-1
115.2 Ob River Basin and Discharge Data	115-1
115.3 Streamflow Characteristics and Change	115-1
115.4 Water Temperature and Thermal Regime	115-4
References	115-5
Chapter 116. Po River Basin	116-1
116.1 River Basin Morphology and Geology, Geometry of the River Network....	116-1
116.2 Climate and Meteorology. Genesis of Extreme Events and Droughts	116-1
116.3 Monitoring Networks	116-3
116.4 Hydrological Balance in the Po River Basin: Exploitation of Water Resources and Sustainability.....	116-3
116.5 The River Regime: Variability, Seasonality, Long-Term Patterns	116-3
116.6 History of Po River Floods	116-3
116.7 Flood Hazard Mitigation Along the Course of the Po River.....	116-4
116.8 Conclusion	116-4
References	116-4
Chapter 117. River Thames Basin	117-1
117.1 Introduction.....	117-1
117.2 The Thames Basin	117-1
117.3 Hydrometric Measurement in the Thames Basin	117-1
117.4 Droughts and Alleviation Measures	117-2
117.5 Floods and Flood Risk	117-3
117.6 Research and Forecasting Initiatives	117-4
117.7 Trends in Runoff Patterns.....	117-4
117.8 Conclusion	117-4
Acknowledgments	117-6

References	117-6
Useful Websites.....	117-6
Chapter 118. Managing Water in an Arid Land: The Murray Darling Basin, Australia	118-1
118.1 Introduction	118-1
118.2 The Murray Darling Basin	118-2
118.3 The Changing Hydrology of the Murray Darling Basin	118-3
118.4 Potential for Ecosystem Collapse	118-5
118.5 The Policy Response	118-5
118.6 What Future Do We Want for the Basin Anyway?	118-6
Conclusion	118-7
References	118-7
Useful Websites	118-9
Chapter 119. The Great Lakes System.....	119-1
119.1 Introduction to the Great Lakes Hydrological System.....	119-1
119.2 The Great Lakes Water Budget	119-2
119.3 Great Lakes Water levels.....	119-5
Acknowledgments	119-5
References	119-5
Chapter 120. The East African Great Lakes	120.1
120.1 Introduction	120.1
120.2 Lake Victoria.....	120.1
120.3 Lake Tanganyika	120.3
120.4 Lake Malawi	120.4
120.5 Lake Albert.....	120.5
120.6 Lake Turkana	120.6
120.7 Lake Kivu.....	120.7
120.8 Lake Edward.....	120.8
References	120.9
Chapter 121. Aral Sea Basin	121-1
121.1 Introduction.....	121-1
121.2 Subsurface Flux Changes and Interactions with the Shrinking Sea	121-1
121.3 Surface Flux Changes and Interactions with Climate Change.....	121-2
121.4 Opportunities and Challenges for Water Quantity and Quality Management.....	121-3
121.5 Conclusion	121-4
References	121-4
Chapter 122. Baltic Sea Basin	122-1
122.1 Introduction.....	122-1
122.2 Physiography and Hydroclimatology.....	122-1
122.3 Hydrology and Water Balance	122-4
122.4 Water Quality.....	122-6
122.5 Future Developments	122-8
122.6 Summary.....	122-9
Acknowledgments	122-9
References	122-9
Chapter 123. Black Sea Basin	123-1
123.1 Introduction.....	123-1
123.2 Geographical Location and Basic Morphometric Characteristics	123-1
123.3 Hydrological Conditions.....	123-1
References	123-5
Chapter 124. The Caspian Sea Basin	124-1
124.1 Introduction.....	124-1
124.2 The Caspian Sea Watershed Area.....	124-1
124.3 The Volga River	124-1
124.4 Physicogeographical Conditions of the Caspian Sea.....	124-3
124.5 Hydrometeorology and Climate.....	124-3
124.6 Physical Oceanography.....	124-3
124.7 Sea Level Variability.....	124-4

124.8	Marine Chemistry.....	124-4
124.9	Marine Biology and Resources	124-5
124.10	Ecological Problems	124-5
124.11	Oil Pollution of the Sea.....	124-6
124.12	Seismic Activity.....	124-7
124.13	Desertification.....	124-7
124.14	Conclusion	124-7
	Acknowledgments	124-7
	References	124-7
	PART 9. Applications and Design	125-1
	Chapter 125. Design Rainfall	125-3
125.1	Purpose of Design Rainfalls.....	125-3
125.2	Constructing Databases of Rainfall to Derive Design Rainfalls	125-4
125.3	AMS Versus PDS	125-5
125.4	Appropriate Probability Distributions	125-5
125.5	Regionalization.....	125-6
125.6	Deriving Sub-Daily and Sub-Hourly IDF Relationships.....	125-7
125.7	Scaling Relationships in Design Rainfalls	125-7
125.8	Developing Design Rainfall Grids	125-8
125.9	Uncertainty in Design Rainfall Estimates	125-8
125.10	Design Temporal Patterns	125-8
125.11	Design Spatial Patterns.....	125-9
125.12	Implications of Temperature Linked Non-Stationarity on the Design Rain..	125-10
	Acknowledgments	125-11
	References	125-11
	Chapter 126. Probable Maximum Precipitation.....	126-1
126.1	Introduction.....	126-1
126.2	Deterministic Method of Estimation of PMP	126-1
126.3	Probabilistic Method of Estimation of PMP	126-10
126.4	Generalized Versus Basin-Specific PMP Estimates	126-13
126.5	All-Season Versus Seasonal PMP Estimates	126-13
126.6	Orographic Effects	126-13
126.7	Spatial Variation of PMP.....	126-13
126.8	Temporal Distribution of PMP—Development of PMS	126-14
126.9	Seasonal Variation of PMP	126-16
126.10	Cautionary Notes on the Procedures for Estimation of New Set of PMP	126-16
	References	126-17
	Chapter 127. Runoff Prediction in Ungauged Basins	127-1
127.1	The Prediction in Ungauged Basins Problem	127-1
127.2	Best Practice Recommendations for Predicting Runoff in Ungauged Basins	127-1
127.3	Prediction of Floods in Ungauged Basins	127-2
127.4	Prediction of Low Flows in Ungauged Basins	127-3
127.5	Prediction of Runoff Hydrographs in Ungauged Basins	127-4
127.6	Where to Go from Here.....	127-5
	Acknowledgments	127-7
	References	127-7
	Chapter 128. Stochastic Streamflow Simulation and Forecasting ..	128.1
128.1	Introduction.....	128. 1
128.2	Stochastic Simulation of Streamflow	128. 1
128.3	Nonparametric Time Series Models	128. 2
128.4	Multisite Streamflow Simulation	128. 3
128.5	Nonstationary Streamflow Simulation	128. 3
128.6	Streamflow Forecasting	128. 4
128.7	Stochastic Weather Generators	128. 4
128.8	Software and Resources	128. 5
	References	128. 5

Chapter 129. Flood Forecasting and Flash Flood Forecasting— Special Considerations in Hydrologic Modeling for the Expressed Purpose of Flood and Flash Flood Forecasting	129-1
129.1 Introduction	129-1
129.2 Real-Time Data Requirements and Forecasts and Data Quality Control	129-1
129.3 Computational Efficiency and Latency Requirements	129-3
129.4 Data Assimilation and/or Adjusting Model Inputs, States, and Outcomes	129-3
129.5 Use of Future Weather	129-3
129.6 Requirements for Regulation Information	129-3
129.7 Flood-Control and Water-Supply Reservoirs	129-4
129.8 Reliability and Stability Requirements	129-4
129.9 Understanding and Conveying Uncertainty	129-4
129.10 Lead Time Considerations and Requirements	129-4
129.11 Temporal (Time Step) Requirements	129-4
129.12 Dissemination and Coordination with Customers, Partners, and the General Public	129-4
129.13 Applications Related to Flash Flooding	129-4
129.14 Special Temporal (Time Step) Requirements	129-4
129.15 Automated Data-Analysis Requirements.....	129-5
129.16 Automated Data Assimilation	129-5
129.17 Ungaged Watershed Application	129-5
129.18 Identification of Highly Vulnerable/at Risk Locations.....	129-5
References	129-5
Chapter 130. Reservoir Operation Design.....	130-1
130.1 Introduction	130-1
130.2 Reservoir Planning and Design	130-1
130.3 Reservoir Operation.....	130-3
130.4 Future Trends in Reservoir Operation Design	130-6
130.5 Conclusion	130-6
References	130-7
Chapter 131. Floodplain Management.....	131-1
131.1 Responses to Flood Risk.....	131-1
131.2 Evolution of Floodplain Management Practices	131-2
131.3 Concepts and Methods	131-2
131.4 Certification in Floodplain Management	131-3
131.5 Summary of Issues and Needed Advances	131-3
References	131-3
Chapter 132. Storm Water Management, Best Management Practices, and Low-Impact Development.....	132-1
132.1 Introduction	132-1
132.2 The Need for Stormwater Management.....	132-2
132.3 Specific BMPs.....	132-3
132.4 Analysis	132-4
132.5 Safety.....	132-4
References	132-4
Chapter 133. Flood Proofing and Infrastructure Development	133-1
133.1 Introduction to Flood Proofing and Infrastructure Development	133-1
Acknowledgment	133-9
References	133-9
Chapter 134. Environmental Flows	134-1
134.1 Introduction	134-1
134.2 Evolution of Environmental Flow Concept	134-2
134.3 Trade-offs in Development and Conservation.....	134-2
134.4 Estimation of Environmental Flows	134-2
134.5 Methodologies for Assessment of Environmental Flow Requirement	134-3
134.6 Implementation of EF	134-6
134.7 Environmental Flows in IWRM	134-7
134.8 Future Challenges.....	134-7
References	134-7

Chapter 135. Drainage and Culvert Design.....	135-1
135.1 Introduction.....	135-1
135.2 Fundamentals of Design	135-1
135.3 Design Procedure	135-4
135.4 Potential Impact of Climate Change on Culvert Design and Operation	135-6
135.5 Sustainable Design	135-6
References	135-6
Chapter 136. Wetland and River Restoration	136-1
136.1 Introduction.....	136-1
136.2 Definitions	136-1
136.3 The Restoration Process	136-2
136.4 Approaches to Wetland and River Restoration	136-3
136.5 Advancing the Science and Practice of Stream and Wetland Restoration.....	136-6
Acknowledgment	136-7
References	136-7
Chapter 137. Institutional Framework for Water Management.....	137-1
137.1 Sustainable Integrated Water Management.....	137-1
137.2 Water Management in Texas: An Illustrative Case Study	137-1
137.3 Water Management Communities.....	137-1
137.4 Federal Agency Programs	137-3
137.5 State Water Resources Planning.....	137-4
137.6 Water Allocation	137-4
137.7 Environmental Management	137-5
137.8 Flood Mitigation.....	137-6
137.9 Institutional Aspects of Computer Modeling.....	137-6
137.10 Conclusion	137-7
References	137-7
Chapter 138. Peak Water, Virtual Water, and Water Footprints: New Definitions and Tools for Water Research and Policy.....	138-1
138.1 Introduction.....	138-1
138.2 Peak Water	138-2
138.3 Comparison of Peak Production in Oil and Water.....	138-3
138.4 Water Transfers and the Concept of Virtual Water	138-4
138.5 Water Footprints.....	138-6
138.6 Soft Water Paths	138-7
138.7 Conclusion	138-7
References	138-8
Chapter 139. Transboundary Water Management	139-1
139.1 Introduction.....	139-1
139.2 Water Conflict	139-1
139.3 Sources of Water Conflict.....	139-2
139.4 International Water Conflicts Versus National Water Conflicts.....	139-2
139.5 Resolving Water Conflicts	139-2
139.6 The Importance of Institutional Capacity	139-3
139.7 Hydro-Hegemony.....	139-3
139.8 International Water Law.....	139-3
139.9 Third Party Involvement.....	139-3
139.10 Future Directions and Ways to Address New Problems	139-4
139.11 Conclusion	139-4
Acknowledgment	139-4
References	139-4
Chapter 140. Integrated River Basin Management.....	140-1
140.1 Integrated River Basin Management: A Framework and Process	140-1
140.2 Elements of IRBM	140-1
140.3 Historical Development	140-2
140.4 Institutional Arrangements for IRBM.....	140-2
140.5 Technical Concepts and Methods.....	140-4
140.6 Case Studies.....	140-5
140.7 Summary.....	140-6
References	140-7