Chow’s Handbook of Applied Hydrology
About the Author

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.
## Contents in Brief

<table>
<thead>
<tr>
<th>Part</th>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part 1</td>
<td>Fundamentals</td>
<td>1.1</td>
</tr>
<tr>
<td>Part 2</td>
<td>Data Collection and Processing</td>
<td>4.1</td>
</tr>
<tr>
<td>Part 3</td>
<td>Methods</td>
<td>12.1</td>
</tr>
<tr>
<td>Part 4</td>
<td>Hydrologic Processes and Modeling</td>
<td>37.1</td>
</tr>
<tr>
<td>Part 5</td>
<td>Sediment and Pollutant Transport</td>
<td>63.1</td>
</tr>
<tr>
<td>Part 6</td>
<td>Hydrometeorologic and Hydrologic Extremes</td>
<td>73.1</td>
</tr>
<tr>
<td>Part 7</td>
<td>Systems Hydrology</td>
<td>81.1</td>
</tr>
<tr>
<td>Part 8</td>
<td>Hydrology of Large River and Lake Basins</td>
<td>93.1</td>
</tr>
<tr>
<td>Part 9</td>
<td>Applications and Design</td>
<td>127.1</td>
</tr>
<tr>
<td>Part 10</td>
<td>Future</td>
<td>151.1</td>
</tr>
</tbody>
</table>
For online supplements and color versions of images, please go to www.mhprofessional.com/handbookofappliedhydrology
## Contents

<table>
<thead>
<tr>
<th>Contributors</th>
<th>xxxiii</th>
</tr>
</thead>
<tbody>
<tr>
<td>International Advisory Board</td>
<td>xliii</td>
</tr>
<tr>
<td>Practitioner Advisory Board</td>
<td>xlv</td>
</tr>
</tbody>
</table>

### 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

### 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 Closing Remarks .................................. 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 Conclusions ...................................... 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
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
Acknowledgement ............................................... 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 Outliers 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

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 A Priori Filtering of Time Series 19-4
19.6 Distribution of a Breakpoint 19-4
19.7 Conclusions 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 Concluding Remarks 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 22-5
22.6 Validation Techniques 22-10

References 22-11

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 Conclusions 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 Conclusions 24-5
24.5 Acknowledgments 24-5
24.6 Appendix: Literature Trend Analysis 24-5

References 24-5

Chapter 25. Nonparametric Methods 25-1

Introduction 25-1
25.1 Definitions 25-1
25.2 Methods 25-2
25.3 Applications 25-3
25.4 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 H-SSSI Processes and Multi-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 Conclusions .................................................... 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
References .................................................................................................................. 31-8
# CONTENTS

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 Closing Remarks ....................................... 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
Reference .................................................... 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 Conclusions ............................ 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 Closing Remarks ..................................... 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 Conclusions .......................................... 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 Concluding Remarks .................................. 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
Acknowledgement ..................................................................... 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 ........................................ 42-2
42.3 Outstanding Problems and Directions for Future Work ........ 42-10
Acknowledgements .................................................................... 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 ... 47-1
  47.3 Investigation 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
### Chapter 53. Waterlogging and Salinization

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 Concluding Remarks ........................................ 53-6
References ................................................................... 53-7

### Chapter 54. Surface Water–Groundwater Interactions: Integrated Modeling of a Coupled System

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 Conclusions ................................................... 54-10
References ................................................................... 54-12

### Chapter 55. Seawater Intrusion in Coastal Aquifers: Concepts, Mitigation, and Simulation

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 Conclusions ................................................... 55-9
References ................................................................... 55-9

### Chapter 56. Regional Land Subsidence Caused by the Compaction of Susceptible Aquifer Systems Accompanying Groundwater Extraction

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 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 Concluding Remarks ........................................ 57-7
References ................................................................... 57-8

### Chapter 58. Catchment Classification and Regionalization

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 Closing Remarks ............................................. 58-5
58.6 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 & 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 Conclusions ........................................................... 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 Schemas ......................................... 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
Chapter 71. Transport of Biochemicals and Microorganisms

71.1 Introduction ........................................................................................................... 71-1
71.2 Biochemicals and Microorganisms ...................................................................... 71-1

References .................................................................................................................... 71-1
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 of 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
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
Acknowledgements ............................................ 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
Acknowledgements .................................................................. 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 Anthropic Activities 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 Concluding Remarks ............................................... 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
Acknowledgement ................................................................... 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 Climate Change Impacts on Basin Hydrology ................. 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 Concluding Remarks ............................................... 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 Concluding Remarks ............................................... 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 Closing Remarks .................................................... 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
<table>
<thead>
<tr>
<th>Chapter 112. St. Lawrence River Basin</th>
<th>112-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>112.1 Introduction</td>
<td>112-1</td>
</tr>
<tr>
<td>112.2 Characteristics of the St. Lawrence River and its Basin</td>
<td>112-1</td>
</tr>
<tr>
<td>112.3 Hydrological Characteristics of the River</td>
<td>112-4</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>112-5</td>
</tr>
<tr>
<td>References</td>
<td>112-5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 113. River Rhine Basin</th>
<th>113-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>113.1 Introduction</td>
<td>113-1</td>
</tr>
<tr>
<td>113.2 Climate</td>
<td>113-1</td>
</tr>
<tr>
<td>113.3 Water Balance in the Rhine Basin</td>
<td>113-4</td>
</tr>
<tr>
<td>113.4 Long-Term Variability of Hydrometeorological Variables in the Rhine Basin</td>
<td>113-4</td>
</tr>
<tr>
<td>113.5 Discharge Characteristics in Longitudinal Profile</td>
<td>113-5</td>
</tr>
<tr>
<td>113.6 The Runoff Regime of the Rhine</td>
<td>113-6</td>
</tr>
<tr>
<td>113.7 Changes in the Runoff Characteristics of Rhine Since the Beginning of the Twentieth Century</td>
<td>113-9</td>
</tr>
<tr>
<td>113.8 Changes in the Runoff Regime of the Upper Rhine</td>
<td>113-10</td>
</tr>
<tr>
<td>113.9 Changes in the Runoff Regime of the Middle and Lower Rhine</td>
<td>113-10</td>
</tr>
<tr>
<td>113.10 Development in Extreme Runoff Situations: Flood</td>
<td>113-10</td>
</tr>
<tr>
<td>113.11 Development in Extreme Runoff Situations: Low Water</td>
<td>113-10</td>
</tr>
<tr>
<td>Acknowledgment</td>
<td>113-10</td>
</tr>
<tr>
<td>References</td>
<td>113-10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 114. Danube River Basin</th>
<th>114-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>114.1 Introduction</td>
<td>114-1</td>
</tr>
<tr>
<td>114.2 History of the River System</td>
<td>114-1</td>
</tr>
<tr>
<td>114.3 Climate, Drainage Characteristics, and Hydrology</td>
<td>114-2</td>
</tr>
<tr>
<td>114.4 Problem faced</td>
<td>114-3</td>
</tr>
<tr>
<td>114.5 Scope of Future Development (2 pages)</td>
<td>114-5</td>
</tr>
<tr>
<td>References</td>
<td>114-5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 115. Ob River Basin</th>
<th>115-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>115.1 Introduction</td>
<td>115-1</td>
</tr>
<tr>
<td>115.2 Ob River Basin and Discharge Data</td>
<td>115-1</td>
</tr>
<tr>
<td>115.3 Streamflow Characteristics and Change</td>
<td>115-1</td>
</tr>
<tr>
<td>115.4 Water Temperature and Thermal Regime</td>
<td>115-4</td>
</tr>
<tr>
<td>References</td>
<td>115-5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 116. Po River Basin</th>
<th>116-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>116.1 River Basin Morphology and Geology, Geometry of The River Network</td>
<td>116-1</td>
</tr>
<tr>
<td>116.2 Climate and Meteorology: Genesis of Extreme Events and Droughts</td>
<td>116-1</td>
</tr>
<tr>
<td>116.3 Monitoring Networks</td>
<td>116-3</td>
</tr>
<tr>
<td>116.4 Hydrological Balance in the Po River Basin. Exploitation of Water Resources and Sustainability</td>
<td>116-3</td>
</tr>
<tr>
<td>116.5 The River Regime. Variability, Seasonality, Long-Term Patterns</td>
<td>116-3</td>
</tr>
<tr>
<td>116.6 History of Po River Floods</td>
<td>116-3</td>
</tr>
<tr>
<td>116.7 Flood Hazard Mitigation Along the Course of the Po River</td>
<td>116-4</td>
</tr>
<tr>
<td>116.8 Conclusions</td>
<td>116-4</td>
</tr>
<tr>
<td>References</td>
<td>116-4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 117. River Thames Basin</th>
<th>117-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>117.1 Introduction</td>
<td>117-1</td>
</tr>
<tr>
<td>117.2 The Thames Basin</td>
<td>117-1</td>
</tr>
<tr>
<td>117.3 Hydrometric Measurement in the Thames Basin</td>
<td>117-1</td>
</tr>
<tr>
<td>117.4 Droughts and Alleviation Measures</td>
<td>117-2</td>
</tr>
<tr>
<td>117.5 Floods and Flood Risk</td>
<td>117-3</td>
</tr>
<tr>
<td>117.6 Research and Forecasting Initiatives</td>
<td>117-3</td>
</tr>
<tr>
<td>117.7 Trends in Runoff Patterns</td>
<td>117-4</td>
</tr>
<tr>
<td>117.8 Concluding Remarks</td>
<td>117-4</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>117-4</td>
</tr>
</tbody>
</table>
xxvi CONTENTS

<table>
<thead>
<tr>
<th>Chapter 124. Marine Chemistry</th>
<th>124-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 124. Marine Biology and Resources</td>
<td>124-5</td>
</tr>
<tr>
<td>Chapter 124. Ecological Problems</td>
<td>124-5</td>
</tr>
<tr>
<td>Chapter 124. Oil pollution of the Sea</td>
<td>124-6</td>
</tr>
<tr>
<td>Chapter 124. Seismic Activity</td>
<td>124-7</td>
</tr>
<tr>
<td>Chapter 124. Desertification</td>
<td>124-7</td>
</tr>
<tr>
<td>Chapter 124. Conclusions</td>
<td>124-7</td>
</tr>
</tbody>
</table>

Acknowledgements .................................................... 124-7
References .................................................................. 124-7

Chapter 125. Design Rainfall ........................................ 125-1

125.1 Purpose of Design Rainfalls .................................... 125-1
125.2 Constructing Databases of Rainfall to Derive Design Rainfalls 125-2
125.3 AMS vs PDS ....................................................... 125-3
125.4 Appropriate Probability Distributions ........................... 125-3
125.5 Regionalization ................................................. 125-4
125.6 Deriving Sub-Daily and Sub-Hourly IDF Relationships ........ 125-5
125.7 Scaling Relationships in Design Rainfalls ..................... 125-5
125.8 Developing Design Rainfall Grids ............................. 125-6
125.9 Uncertainty in Design Rainfall Estimates ..................... 125-6
125.10 Design Temporal Patterns ....................................... 125-6
125.11 Design spatial patterns ......................................... 125-7
125.12 Implications of Temperature Linked Non-Stationarity on the Design Rain ........................................... 125-8

Acknowledgements .................................................... 125-9
References .................................................................. 125-9

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 Developing Design Rainfall Grids—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

PART 9. Applications and Design .................................... 127-1

Chapter 127. Runoff Prediction in Ungauged Basins ............. 127-3

127.1 The Prediction in Ungauged Basins Problem ............... 127-3
127.2 Best Practice Recommendations for Predicting Runoff in Ungauged Basins ..................................................... 127-3
127.3 Prediction of Floods in Ungauged Basins ..................... 127-4
127.4 Prediction of Low Flows in Ungauged Basins ............... 127-5
127.5 Prediction of Runoff Hydrographs in Ungauged Basins ..... 127-6
127.6 Where To Go From Here ........................................ 127-7

Acknowledgements .................................................... 127-9
References .................................................................. 127-9

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 Customer, 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 Conclusions .................................................................................... 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
Acknowledgement ............................................................................. 133-9
References ......................................................................................... 133-9

Chapter 134. Environmental Flows .................................................. 134-1
134.1 Introduction .................................................. 134-1
134.2 Evolution of Environmental Flows 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 Flows 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 Introduction ........................................ 135-1  
135.2 Fundamentals of Design .......................... 135-4  
135.3 Design Procedure .................................. 135-6  
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 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  
Acknowledgement .......................................... 136-7  
References .................................................. 136-7

## Chapter 137. Institutional Framework for Water Management

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 Conclusions ......................................... 137-7  
References .................................................. 137-7


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 Conclusions ......................................... 138-7  
References .................................................. 138-8

## Chapter 139. Transboundary Water Management

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  
Acknowledgement .......................................... 139-4  
References .................................................. 139-4

## Chapter 140. Integrated River Basin Management

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
Chapter 141. Conflict Resolution ................................. 141-1
141.1 Conflict Exists Everywhere ................................. 141-1
141.2 Game Theoretic Models for Conflict Analysis .............. 141-1
141.3 Graph Model for Conflict Resolution ....................... 141-1
141.4 Fair Water Allocation ........................................ 141-2
141.5 Compliance Models ........................................... 141-4
141.6 Agent-Based Modeling and Simulation ...................... 141-5
141.7 Summary ....................................................... 141-5
References .............................................................. 141-5

Chapter 142. Long-distance Water Transfers ...................... 142-1
142.1 Introduction ..................................................... 142-1
142.2 Transfers Among Basins, Regions and Countries—Achievements and Concerns ............................. 142-1
Further Thoughts ..................................................... 142-6
References .............................................................. 142-6

Chapter 143. The Indian River-Linking Program ................. 143-1
143.1 Introduction ..................................................... 143-1
143.2 India's Water Resources and the River-Linking Plan .......... 143-1
143.3 Prognosis and Implication .................................. 143-5
143.4 Conclusions .................................................... 143-8
Acknowledgment ..................................................... 143-8
Reference ............................................................. 143-8

Chapter 144. Irrigation Scheduling and Management ............ 144-1
144.1 Introduction ..................................................... 144-1
144.2 Soil-Plant-Atmosphere Interaction .......................... 144-2
144.3 On-farm Irrigation Scheduling ................................ 144-7
144.4 Canal Irrigation Scheduling .................................... 144-7
144.5 Conclusions ..................................................... 144-8
144.6 Research Needs ................................................ 144-8
References .............................................................. 144-8

Chapter 145. Rainwater Harvesting and Groundwater Recharge ... 145-1
145.1 Introduction ..................................................... 145-1
145.2 Ancient Methods of Water Harvesting ....................... 145-1
145.3 Watershed Development ...................................... 145-2
145.4 Rainwater-Harvesting Structures ............................ 145-3
145.5 Assessment of Rainwater Harvesting Using Remote Sensing and GIS ........................ ...................... 145-7
145.6 Rainwater Harvesting Studies a Global Perspective ....... 145-7
References .............................................................. 145-9

Chapter 146. Reuse-Reclaimed Water in Managed Aquifer Recharge 146-1
146.1 Introduction ..................................................... 146-1
146.2 Treatment Mechanisms in Natural Systems .................. 146-2
146.3 Managed Aquifer Recharge ................................... 146-2
146.4 Water Quality Considerations for Managed Aquifer Recharge .. 146-3
146.5 Surface Spreading .............................................. 146-3
146.6 Injection Wells .................................................. 146-4
146.7 Recovery of Reclaimed Water through Aquifer Storage and Recovery ...................... 146-5
146.8 Subsurface Geochemical Processes ........................... 146-6
146.9 Summary ....................................................... 146-6
References .............................................................. 146-6

Chapter 147. River Bank Filtration ................................ 147-1
147.1 Introduction ..................................................... 147-1
147.2 River Hydrology ................................................ 147-1
147.3 Potential of River Bank Filtration ............................ 147-2
147.4 Simulating RBF Quality ....................................... 147-3
147.5 Optimizing Distance of Well from the River ................ 147-6
147.6 River Bank Filtration Sites .................................... 147-6
147.7 Summary ....................................................... 147-7
References .............................................................. 147-7
### Chapter 153. Extraterrestrial Water

153.1 Introduction ........................................................... 153-1
153.2 The Origin of the Earth's Water .................................................. 153-1
153.3 Water in our Solar System ......................................................... 153-1
153.4 Water Beyond our Solar System ............................................... 153-3
153.5 Summary ........................................................................... 153-4

References ............................................................................. 153-4

### Chapter 154. Water Security

154.1 Availability of Freshwater around the World ............................ 154-1
154.2 Current State of Water Affairs .................................................. 154-1
154.3 Water Security—the Discourse .................................................. 154-3
154.4 Global Availability of Groundwater .......................................... 154-3
154.5 Water Security as Part of Economic Security ......................... 154-4
154.6 Managing Water in a Changing World .................................... 154-4
154.7 Meeting the Water Gap: Unlocking the Potential of Green Water........................................................................... 154-4

Conclusion ............................................................................... 154-5
Acknowledgments ...................................................................... 154-5
References ............................................................................. 154-5

### Chapter 155. Social Hydrology

155.1 Water and Human Beings .......................................................... 155-1
155.2 What is Social Hydrology? ......................................................... 155-3
155.3 Great Hydraulic Mission .............................................................. 155-4
155.4 Nature's Talk Back ................................................................. 155-4
155.5 Evolution of Social Hydrology as a New Discipline .................. 155-6
155.6 Challenges Ahead in Water Management .................................. 155-7
155.7 Recent Trends and Developments in Social Hydrology ............. 155-8
155.8 Climate Change and Future Issues in Social Hydrology .......... 155-8
155.9 Future Direction in Social Hydrology ....................................... 155-9

References ............................................................................. 155-10

### Chapter 156. Grand Challenges Facing the Hydrologic Sciences

156.1 Introduction .......................................................... 156-1
156.2 Quality-Differentiated Water Management .................................. 156-1
156.3 Conversion Strategy ............................................................... 156-2
156.4 Scoping the Greater Hydrologic System ................................... 156-2
156.5 Scoping Water Needs ............................................................... 156-3
156.6 Emerging Infrastructure Needs ............................................... 156-3
156.7 Information Systems ............................................................... 156-4
156.8 Prioritization .................................................................... 156-4
156.9 Selected Priority Challenges ..................................................... 156-5
156.10 From Research to Reality ......................................................... 156-6
156.11 Summary and Conclusions ..................................................... 156-6

Acknowledgements .................................................................... 156-6
References ............................................................................. 156-6
Contributors

Benjamin Abban
Department of Civil and Environmental Engineering
University of Tennessee
Knoxville, Tennessee

M. C. Acreman
Centre for Ecology and Hydrology
Crowmarsh Gifford
Wallingford, United Kingdom

Lauren Adams
Center for Watershed Sciences
University of California, Davis
Davis, California

Pradeep Aggarwal
Isotope Hydrology Section
Division of Physical and Chemical Sciences
Department of Nuclear Sciences and Applications
International Atomic Energy Agency (IAEA)
Vienna, Austria

Mohammad Z. Al-Hamdan
Universitas Space Research Association
NASA/ Marshall Space Flight Center
National Space Science Technology Center
Huntsville, Alabama

Doug Alsdorf
Byrd Polar and Climate Research Center
The Ohio State University
Columbus, Ohio

Devendra M. Amaty
USDA Forest Service Center for Forested Wetlands Research
Cordova, South Carolina

Daniel P. Ames
Department of Civil and Environmental Engineering
Brigham Young University
Provo, Utah

Burakon Dmitry Anatolyevich
Department of Environmental Engineering
Krasnoyarsk State Agrarian University
Krasnoyarsk, Russia

Michael Anderson
California Department of Water Resources
Division of Flood Management
Hydrology and Flood Operations Office
Sacramento, California

Mazdak Arabi
Department of Civil and Environmental Engineering
Colorado State University
Fort Collins, Colorado

Luis J. Araguas-Araguas
Isotope Hydrology Section
Division of Physical and Chemical Sciences
Department of Nuclear Sciences and Applications
International Atomic Energy Agency (IAEA)
Vienna, Austria

Mustafa M. Aral
School of Civil and Environmental Engineering
Georgia Institute of Technology
Atlanta, Georgia

Bhavna Arora
Earth Sciences Division
Lawrence Berkeley National Laboratory
Berkeley, California

M. Babbar-Sebens
School of Civil and Construction Engineering
Oregon State University
Corvallis, Oregon

Daniel W. Baker
Department of Civil and Environmental Engineering
Colorado State University
Fort Collins, Colorado

Emanuele Baratti
Department DICEAM
University of Bologna
Bologna, Italy

Donald E. Barke
Department of Civil and Environmental Engineering
University of New Orleans
New Orleans, Los Angeles

Henry Barousse
Louisiana Department of Transportation and Development (Retired)

Robert Bastian
U.S. Environmental Protection Agency
Washington, D.C.

Peter Rauz-Gottweis
Department of Environmental Engineering
Technical University of Denmark
Lyngby, Denmark

Hiroyuki Kato Beaudoin
Earth System Science Interdisciplinary Center
University of Maryland
College Park, Maryland

Kati Bell
Global Practice Leader - Water Reuse
MWH Global
Brentwood, Tennessee

Jorge Luis Belx
BBG - Federal Institute of Hydrology
Koblenz, Germany

Lars Bengtsson
Department of Water Resources Engineering
Lund Institute of Technology
Lund University
Lund, Sweden

Ronnei Berndtsson
Department of Water Resources Engineering
and Center for Middle Eastern Studies
Lund University
Lund, Sweden

Daniela Biondi
Institute of Hydraulic Construction
University of Bologna
Bologna, Italy
CONTRIBUTORS

Brian P. Bledsoe
Department of Civil and Environmental Engineering
Colorado State University
Fort Collins, Colorado

Günter Blöschl
Institute of Hydraulic Engineering
Centre for Water Resource Systems
Institut für Wasserbau und Ingenieurhydromologie
Technische Universität Wien
Wien, Austria

Istvan Bogardi
Department of Civil Engineering
Izmir Institute of Technology
Izmir, Turkey

D. Bolton
NASA/GSFC, Hydrological Sciences Branch
Greenbelt, Maryland

André Bouchard
Hydrology and Ecohydraulic Section
Meteorological Service of Canada
Québec, Canada

Armando Brath
Department DICAM
University of Bologna
Bologna, Italy

Juan Martin Bravo
Instituto de Pesquisas Hidráulicas
Universidade Federal do Rio Grande do Sul
IPHI-UFRGS
Porto Alegre, Brazil

Donald H. Burn
Department of Civil and Environmental Engineering
University of Waterloo
Waterloo, Canada

Aaron R. Byrd
Hydrologic Systems Branch
Coastal and Hydraulics Laboratory
Engineer Research Development Center
U.S. Army Corps of Engineers
Vicksburg, Mississippi

Ximing Cai
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois

Darryl Carlyle-Moses
Department of Geography and Environmental Studies
Thompson Rivers University
Kamloops, Canada

Attilio Castellarin
DICAM - Corruzioni Idrauliche, Università degli Studi di Bologna
Bologna, Italy

Serena Ceola
Department DICAM
University of Bologna
Bologna, Italy

C. P. Cetinkaya
Dokuz Eylül University
Water Resources Management Research and Application Center (SUMER)
Izmir, Turkey

Maria A. Charina
Water Problems Institute of the Russian Academy of Sciences
Moscow, Russia

Futok Chehama
Institut national de la recherche scientifique
Centre Éau-Terre-Environnement
Québec, Canada

Ji Chen
Department of Civil Engineering
The University of Hong Kong
Hong Kong, People's Republic of China

Yang Cheng
Department of Civil and Environmental Engineering
Syracuse University
Syracuse, New York

Nannan Cheng
State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau
Institute of Soil and Water Conservation
Chinese Academy of Sciences and Ministry of Water Resources
Northwest Agriculture and Forest University
Yangling, People's Republic of China

Ekaterina V. Chaprina
Water Problems Institute of the Russian Academy of Sciences
Moscow, Russia

Theodore G. Cleveland
Associate Professor
Department of Civil, Environmental, and Construction Engineering
Texas Tech University
Lubbock, Texas

Walter Collischonn
Instituto de Hydraulic Research
Universidade Federal do Rio Grande do Sul
IPHI-UFRGS
Porto Alegre, Brazil

Zhentao Cong
Department of Hydraulic Engineering
Tsinghua University
Beijing, People's Republic of China

James Connaughton
Richmond, California

Corrado Corradini
Department of Civil and Environmental Engineering
Facolta di Ingegneria
University of Perugia
Perugia, Italy

Alva Couch
Department of Computer Science
Tufts University
Medford, Massachusetts

Norman H. Crawford
Hydrocomp, Inc.
Menlo Park, California

James F. Cruise
Department of Civil and Environmental Engineering
University of Alabama in Huntsville
Huntsville, Alabama

Allegra da Silva
CDM Smith
Denver, Colorado

Baptiste Dafflon
Earth Sciences Division
Lawrence Berkeley National Laboratory
Berkeley, California

Kumer Pial Das
Department of Mathematics
Lamar University
Beaumont, Texas

Claas Davidsen
Department of Environmental Engineering
Technical University of Denmark
Lyngby, Denmark

Rodrigo Canduro Dias de Paiva
Instituto de Hydraulic Research
Federal University of Rio Grande do Sul
Porto Alegre, Brazil

Zhi-Qiang Deng
Department of Civil and Environmental Engineering
Louisiana State University
Baton Rouge, Los Angeles

Georgia Destouni
Department of Physical Geography and Quaternary Geology
Stockholm University
Stockholm, Sweden
Michael DeWeese  
National Weather Service  
North Central River Forecast Center  
Chanhassen, Minnesota

Daniel H. Doctor  
Eastern Geology and Paleoclimate Science Center  
U.S. Geological Survey  
Reston, Virginia

Alessio Domenghetti  
Department DISCAM  
University of Bologna  
Bologna, Italy

A. S. Donigian, Jr.  
AGS TERRA Consultants  
Mountain View, California

Charles W. Downer  
CEERD-HFH  
Coastal and Hydraulics Laboratory  
Vicksburg, Mississippi

André Duizer  
Department of Civil and Environmental Engineering  
Colorado State University  
Fort Collins, Colorado

Jim Dumont  
Water Infrastructure Specialist  
Salt Spring Island, Canada

Dipankar Dwivedi  
Earth Sciences Division  
Lawrence Berkeley National Laboratory  
Berkeley, California

Walter L. Elsberry  
Department of Civil and Environmental Engineering  
University of Alabama in Huntsville  
Huntsville, Alabama

A. Erkan  
Hydrologic Research Laboratory  
Department of Civil and Environmental Engineering  
University of California  
Davis, California

Alvar Escrivá-Bou  
Davis, California

James S. Famiglietti  
NASA Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California

Karen Fang  
School of Civil and Environmental Engineering  
The University of New South Wales  
Sydney, Australia

Liping Fang  
Department of Mechanical and Industrial Engineering  
Faculty of Engineering and Architectural Science  
Ryerson University  
Toronto, Canada

Bonifacio Fernandez and Jorge Gironás  
P.U. Católica de Chile  
Santiago, Chile

Stefan Finsterle  
Earth Sciences Division  
Lawrence Berkeley National Laboratory  
Berkeley, California

Faith A. Fitzpatrick  
Fluvial Geomorphology  
USGS WI Water Science Center  
Middleton, Wisconsin

Darrell Fontane  
Department of Civil and Environmental Engineering  
Colorado State University  
Fort Collins, Colorado

Donald K. Frevert  
Retired Hydraulic Engineer and Team Leader  
Bureau of Reclamation  
Denver, Colorado

Devin L. Galloway  
U.S. Geological Survey  
Indianapolis, Indiana

Timothy S. Gambrel  
Mississippi River Science and Technology Office and Mississippi River Commission  
Mississippi Valley Division  
U.S. Army Corps of Engineers  
Vicksburg, Mississippi

Christian Genest  
Department of Mathematics and Statistics  
McGill University  
Montréal, Canada

Timothy R. Ginn  
Department of Civil and Environmental Engineering  
University of California  
Davis, California

Jorge Gironás  
Departamento de Ingeniería Hidráulica y Ambiental  
Centro de Investigación para la Gestión Integrada de Desastres Naturales (CIGIDEN)  
Centro de Desarrollo Urbano Sustentable (CEDESU)  
Centro Multidisciplinario de Cambio Global  
Pontificia Universidad Católica de Chile  
Santiago, Chile

Peter H. Gleick  
Pacific Institute  
Oakland, California

Narendra Kumar Gontia  
College of Agricultural Engineering and Technology  
Junagadh Agricultural University  
Junagadh, India

Jonathan L. Goodall  
Department of Civil and Environmental Engineering  
University of Virginia  
Charlottesville, Virginia

David C. Goodrich  
USDA-ARS  
Southwest Watershed Research Center  
Tucson, Arizona

R. S. Govindaraju  
Delon and Elizabeth Hampton Hall of Civil Engineering  
Purdue University  
West Lafayette, Indiana

Robert E. Griffin  
Atmospheric Science Department  
Earth System Science Program  
University of Alabama in Huntsville  
Huntsville, Alabama

Neil S. Grigg  
Department of Civil and Environmental Engineering  
Colorado State University  
Fort Collins, Colorado

Andrew D. Gronewold  
NOAA (Great Lakes Environmental Research Laboratory)  
University of Michigan (Civil and Environmental Engineering)  
NOAA-GLERL  
Ann Arbor, Michigan

Georges Gaume  
Commission Internationale du bassin Congo-Oubangui-Sangha  
Kinduass-Gombe, Democratic Republic of the Congo

Orhan Gunduz  
Dokuz Eylul University  
Department of Environmental Engineering  
Izmir, Turkey

H. V. Gupta  
Department of Hydrology and Water Resources  
University of Arizona  
Tucson, Arizona

Semyon M. Guziy  
Institute “Krasnoyarskgidroproekt”  
Krasnoyarsk State Agricultural University  
Krasnoyarsk branch of JSC “SBENYCU”  
Krasnoyarsk, Russia
CONTRIBUTORS

Alan F. Hamlet
Dept. of Civil and Environmental Engineering and Earth Sciences
University of Notre Dame
Notre Dame, Indiana

Cameron Handside
Earth System Science Center
University of Alabama in Huntsville
Huntsville, Alabama

Mohamed M. Hantush
National Risk Management Research Laboratory
U.S. Environmental Protection Agency
Cincinnati, Ohio

Unesch Hantush
Department of Geology
University of Dayton
Dayton, Ohio

Bekki Ward Harjo
Senior Hydrologist, National Weather Service
Arkansas Red Basin River Forecast Center
Tulsa, Oklahoma

Nilgun Harmanlioglu
Water Resources Institute
Dokuz Eylul University
Izmir, Turkey

Julien J. Haroun
School of Mechanical, Aerospace and Civil Engineering
The University of Manchester
Manchester, United Kingdom

Robert Hartman
HIC, NWS
Sacramento, California

Hongming He
Institute of Soil and Water Conservation
Chinese Academy of Sciences and Ministry of Water Resources
Yangling, People's Republic of China

Janet Herman
University of Virginia
Charlottesville, Virginia

Kith W. Hipel
Department of Systems Design Engineering
University of Waterloo
Waterloo, Canada

Yoshinari Hiroshiro
Faculty of Engineering
Department of Civil Engineering
Kyushu University
Fukuoka, Japan

Michael T. Hobbs
National Integrated Drought Information System
NOAA Earth System Research Laboratory
Boulder, Colorado

Robert R. Holmes, Jr.
U.S. Geological Survey
Bozeman, Montana

Jeffrey S. Horsho
Department of Civil and Environmental Engineering
Utah State University
Logan, Utah

Chi Hua Huang
National Soil Erosion Research Laboratory
West Lafayette, Indiana

Denis Arthur Hughes
Institute for Water Research
Rhodes University
Grahamstown, South Africa

Bai Hui
University of California, Davis
Center for Watershed Sciences
One Shields Avenue
Davis, California

Justin Huntington
Desert Research Institute
Division of Hydrologic Sciences
Western Regional Climate Center
Reno, Nevada

John C. Imhoff
AQuA TERRA Consultants
Oxley, Colorado

K. Ishida
Hydrologic Research Laboratory
Department of Civil and Environmental Engineering
University of California
Davis, California

Sharad K. Jain
Water Resources Systems Division
National Institute of Hydrology
Roorkee, India

L. Douglas James
Fairfax, Virginia

A. W. Jayawardena
Department of Civil Engineering
The University of Hong Kong
Hong Kong, People's Republic of China

Kenji Jinno
Kyushu University
Munakata City, Japan

Fiona Johnson
School of Civil and Environmental Engineering
The University of New South Wales
Sydney, Australia

V. Jothiprakash
Department of Civil Engineering
Indian Institute of Technology Bombay
Mumbai, India

Tijana Jovanovic
Department of Civil and Environmental Engineering
The Pennsylvania State University
State College, Pennsylvania

Latif Kalin
School of Forestry and Wildlife Sciences
Auburn University
Auburn, Alabama

Jagath Kaluarachchi
College of Engineering
Professor of Civil and Environmental Engineering
Utah State University
Logan, Utah

R. Karlheiden
Biological and Agricultural Engineering Department
Texas A&M University
College Station, Texas

Laila Kasuri
Chevy Chase, Maryland

Dmitri Kavetski
School of Engineering
University of Newcastle
Callaghan, Australia

M. Levent Kavvas
Department of Civil and Environmental Engineering
University of California
Davis, California

Akira Kawamura
Department of Civil and Environmental Engineering
Tokyo Metropolitan University
Tokyo, Japan

Justin Huntington
Desert Research Institute
Division of Hydrologic Sciences
Western Regional Climate Center
Reno, Nevada

John C. Imhoff
AQuA TERRA Consultants
Oxley, Colorado

K. Ishida
Hydrologic Research Laboratory
Department of Civil and Environmental Engineering
University of California
Davis, California

Sharad K. Jain
Water Resources Systems Division
National Institute of Hydrology
Roorkee, India

L. Douglas James
Fairfax, Virginia

A. W. Jayawardena
Department of Civil Engineering
The University of Hong Kong
Hong Kong, People's Republic of China

Kenji Jinno
Kyushu University
Munakata City, Japan

Fiona Johnson
School of Civil and Environmental Engineering
The University of New South Wales
Sydney, Australia

V. Jothiprakash
Department of Civil Engineering
Indian Institute of Technology Bombay
Mumbai, India

Tijana Jovanovic
Department of Civil and Environmental Engineering
The Pennsylvania State University
State College, Pennsylvania

Latif Kalin
School of Forestry and Wildlife Sciences
Auburn University
Auburn, Alabama

Jagath Kaluarachchi
College of Engineering
Professor of Civil and Environmental Engineering
Utah State University
Logan, Utah

R. Karlheiden
Biological and Agricultural Engineering Department
Texas A&M University
College Station, Texas

Laila Kasuri
Chevy Chase, Maryland

Dmitri Kavetski
School of Engineering
University of Newcastle
Callaghan, Australia

M. Levent Kavvas
Department of Civil and Environmental Engineering
University of California
Davis, California

Akira Kawamura
Department of Civil and Environmental Engineering
Tokyo Metropolitan University
Tokyo, Japan
Soksamnang Keo  
State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau  
Institute of Soil and Water Conservation  
Chinese Academy of Sciences and Ministry of Water Resources  
Northwest Agriculture and Forest University  
Yangling, People’s Republic of China

Greg Kerr  
Office of Water Programs  
University of Wyoming  
Laramie, Wyoming

Martin Koubert  
Agricultural and Biological Engineering  
Purdue University  
West Lafayette, Indiana

Jongho Kwon  
Department of Civil Engineering  
McMaster University  
Hamilton, Canada

C. Prakash Khedun  
Department of Biological and Agricultural Engineering  
Texas A&M University  
College Station, Texas

Max Kibogo  
Department of Civil Engineering  
College of Engineering, Design, Art and Technology (CEDAT)  
Makerere University  
Kampala, Uganda

Thomas R. Kjeldsen  
Department of Architecture and Civil Engineering  
University of Bath  
Bath, United Kingdom

Barbara A. Kleiss  
USACE-Mississippi Valley Division  
Vicksburg, Mississippi

Randal Koster  
Global Modeling and Assimilation Office  
NASA Goddard Space Flight Center  
Greenbelt, Maryland

Andrey Kostianoy  
P.P. Shirshov Institute of Oceanology  
Russian Academy of Sciences  
Moscow, Russia

Demetris Koutrouliannis  
Department of Water Resources and Environmental Engineering  
National Technical University of Athens  
Heronios Polytechneiou  
Zographou, Greece

Peter Krabbe  
BIG - Federal Institute of Hydrology  
Koblenz, Germany

Valentina Krysanova  
Potsdam Institute for Climate Impact Research  
Potsdam  
Germany

Lev Kirshmont  
Laboratory of Water Cycle  
Water Problems Institute  
Russian Academy of Sciences  
Moscow, Russia

George Kuczera  
School of Engineering  
University of Newcastle  
Callaghan, Australia

Bhishon Kumar  
Ex Professional Staff  
Isotope Hydrology Section  
International Atomic Energy Agency (IAEA)  
Vienna, Austria  
Ex Head  
Hydrological Investigations Division  
National Institute of Hydrology  
Roorkee, India

Zhagniec W. Kandrzejewicz  
Institute of Agricultural and Forest Environment  
Polish Academy of Sciences  
Poznan, Poland

John Labadie  
Department of Civil and Environmental Engineering  
Colorado State University  
Fort Collins, Colorado

David Labat  
Geosciences Environnement Toulouse  
Toulouse, France

Venkataraman (Vinukat) Lakshmi  
Department of Earth and Ocean Sciences  
University of South Carolina  
Columbia, South Carolina

Uppanu Lall  
Department of Earth and Environmental Engineering  
Department of Civil Engineering and Engineering Mechanics  
Columbia Water Center  
International Research Institute for Climate and Society  
Columbia University  
New York

Alain Laraque  
Directeur de Recherche en Hydrologie  
GET - UMR CNRS / IRD / UPS - UMR 5563 du CNRS, UMR234 de l’IRD  
Toulouse, France

Magnus Larson  
Department of Water Resources Engineering  
Lund Institute of Technology  
Lund University  
Lund, Sweden

Stanley A. Leake  
U.S. Geological Survey  
Tucson, Arizona

Chiara Lepore  
Ocean and Climate Physics  
Lamont-Doherty Earth Observatory  
Palisades, New York

L. Ruby Leung  
Atmospheric Sciences and Global Change Division  
Pacific Northwest National Laboratory  
Richland, Washington

Benjamin Lord  
Raleigh, North Carolina

Yuju Lu  
State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau  
Institute of Soil and Water Conservation  
Chinese Academy of Sciences and Ministry of Water Resources  
Northwest Agriculture and Forest University  
Yangling, People’s Republic of China

Jay R. Lund  
Center for Watershed Sciences  
Department of Civil and Environmental Engineering  
University of California  
Davos, California

Gil Mahe  
IRD, Laboratoire Hydro Sciences  
Montpellier, France

D. R. MAILLAPULI  
Agricultural and Food Engineering Department  
Indian Institute of Technology Kharagpur  
Kharagpur, India

Terry Marsh  
Centre for Ecology & Hydrology  
Wallington, United Kingdom

Philip Marsh  
Water Science Wilfrid Laurier University  
Waterloo, Canada

José Pedro Matos  
Laboratoire de constructions hydrauliques (LCH)  
Ecolepolytechniquefédérale de Lausanne (EPFL)  
Lausanne, Switzerland
Larry W. Mays  
Arizona State University  
Tempe, Arizona

Richard H. McCuen  
Civil and Environmental Engineering Department  
University of Maryland  
College Park, Maryland

Steven G. McNulty  
Eastern Forest Environmental Threat Assessment Center  
Southern Research Station, USDA Forest Service  
Raleigh, North Carolina

Alihosn Majeed  
Department of Civil and Environmental Engineering  
The Pennsylvania State University  
State College, Pennsylvania

Tarık Merabiene  
Department of Civil and Environmental Engineering  
College of Engineering  
University of Sharjah  
Sharjah, United Arab Emirates

Venkatesh Merwade  
Lyles School of Civil Engineering  
Purdue University  
West Lafayette, Indiana

Srikanta Mishra  
Water Problems Institute of the Russian Academy of Sciences  
Moscow, Russia

Ilona E. Mladenova  
NASA/GSFC, Hydrological Sciences Branch  
Greenbelt, Maryland

Binayak P. Mohanty  
Biological and Agricultural Engineering  
Texas A&M University  
College Station, Texas

Kazuro Momii  
Faculty of Agriculture  
Kagoshima University  
Korimoto, Japan

Alberto Montanari  
Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali  
University of Bologna  
Bologna, Italy

B. Morbidelli  
Department of Civil and Environmental Engineering  
Pergusa University  
Pergusa, Italy

Rasuul Mukhopadhyay  
National Practice Leader | Water Resources  
North American Infrastructure  
Jacobs Engineering Group, Inc.  
Dallas, Texas

Daren Musabih  
Department of Water Resources Engineering  
Lund Institute of Technology  
Lund University  
Lund, Sweden

Kei Nakagawa  
Nagasaki University  
Graduate School of Fisheries Science and Environmental Studies  
Nagasaki University  
Nagasaki, Japan

Mohamed K. Nasser  
Department of Civil and Environmental Engineering  
University of California  
Davis, California

Grey S. Nearing  
NASA/GSFC  
Hydrological Sciences Branch  
Greenbelt, Maryland

W. W. Ng  
Department of Civil Engineering  
Lakehead University  
Thunder Bay, Canada

John Nielsen-Gammon  
Department of Atmospheric Sciences  
Texas A&M University  
College Station, Texas

Jun Niu  
College of Water Resources and Civil Engineering  
China Agricultural University  
Beijing, People’s Republic of China

Robert K. Niven  
School of Civil Engineering and Geosciences  
Newcastle University  
Newcastle upon Tyne, United Kingdom

P. E. O’Connell  
School of Civil Engineering and Geosciences  
Newcastle University  
Newcastle upon Tyne, United Kingdom

Greg O’Donnell  
School of Civil Engineering and Geosciences  
Newcastle University  
Newcastle upon Tyne, United Kingdom

Robert Oschepke  
United States Army Corps of Engineers (Retired)

Fred L. Ogden  
Department of Civil and Architectural Engineering and  
Haub School of Environment and Natural Resources  
University of Wyoming  
Laramie, Wyoming

N. Olara  
Department of Civil and Architectural Engineering  
University of Wyoming  
Laramie, Wyoming

C. S. P. Ojha  
Department of Civil Engineering  
Indian Institute of Technology Roorkee  
Roorkee, India

Taha B. M. J. Ouarda  
Institute Center for Water and Environment (iWATER)  
Masdar Institute of Science and Technology  
Abu Dhabi, United Arab Emirates

Hisashi Ozawa  
Graduate School of Integrated Arts and Sciences  
Hiroshima University  
Higashi-Hiroshima, Japan

Umed S. Panu  
Department of Civil Engineering  
Lakehead University  
Thunder Bay, Canada

Simon Michael Papalexiou  
Department of Water Resources and Environmental Engineering  
National Technical University of Athens  
Herion Polytechniou  
Zographou, Greece
Thanos Papapaniolaou  
Department of Civil and Environmental Engineering  
University of Tennessee  
Knoxville, Tennessee

Sandra Pavlovic  
University Corporation for Atmospheric Research  
Boulder, Colorado

Patra Plakova  
Institute of Hydrology  
Slovak Academy of Sciences  
Bratislava, Slovakia

Angela Pelc  
Department of Civil and Environmental Engineering  
University of Alabama  
Tuscaloosa, Alabama

Mauri Polto  
Department of Environmental Science  
Nichols College  
Dudley, Massachusetts

Silvio J. Pereira-Cardenal  
COWI A/S  
Lyngby, Denmark

Magnus Persson  
Department of Water Resources Engineering  
Lund Institute of Technology  
Lund University  
Lund, Sweden

Masih Permal  
Department of Hydrology  
Indian Institute of Technology Roorkee  
Roorkee, India

Jacob Petersen-Perlman  
Oregon State University  
Corvallis, Oregon

Christa D. Peters-Lidard  
Hydrological Sciences Laboratory  
NASA Goddard Space Flight Center  
Greenbelt, Maryland

Hai V. Pham  
Department of Civil and Environmental Engineering  
Louisiana State University  
Baton Rouge, Louisiana

Mikolaj Piniewski  
Warsaw University of Life Sciences  
Warsaw, Poland

Paulo Régis Monteiro Pontes  
Instituto de Pesquisas Hidráulicas  
Universidade Federal do Rio Grande do Sul  
IPH-UFRGS  
Porto Alegre, Brazil

Erik C. Porse  
UCLA Institute of the Environment and Sustainability  
Los Angeles, California

Nawal Raj Pradhan  
CEERD-HEH  
Cisatul and Hydraulic Laboratory  
Vicksburg, Mississippi

James Pratie  
Hydrologic Engineer  
Bureau of Reclamation  
Upper Colorado Regional Office  
Denver Federal Center  
Denver, Colorado

K. S. H. Prasad  
Department of Civil Engineering  
Indian Institute of Technology Roorkee  
Roorkee, India

Roland K. Price  
UNESCO-IHE, Institute for Water Education  
Delft, The Netherlands

Fernando Falco Pruski  
Department of Agricultural Engineering  
Federal University of Viçosa  
Viçosa, Brazil

Manuel Pulido-Velazquez  
Research Institute of Water and Environmental Engineering (IIAMA)  
Universitat Politècnica de València  
Valencia, Spain

Narendra Singh Raghuvanshi  
Agricultural and Food Engineering Department  
Indian Institute of Technology Kharagpur  
Kharagpur, India

Ataur Rahman  
Water and Environmental Engineering  
School of Computing, Computing and Mathematics  
Western Sydney University  
Penrith, Australia

Balaji Rajagopalan  
Department of Civil, Environmental and Architectural Engineering  
University of Colorado  
Boulder, Colorado

H. D. Ranik  
Department of Soil and Water Engineering  
College of Agricultural Engineering and Technology  
Junagadh Agricultural University  
Junagadh, India

Liliang Ren  
International Office  
Hohai University  
Nanjing, People's Republic of China

Ben Renard  
School of Engineering  
University of Newcastle  
Callaghan, Australia

Pedro J. Ribeiro  
National Weather Service  
North Central River Forecast Center  
Chanhassen, Minnesota

Mebdi Rezaiianzadeh  
School of Forestry and Wildlife Sciences  
Auburn University  
Auburn, Alabama

Niels Riegs  
DHI  
Hørsholm, Denmark

Matthew Rudell  
Hydrological Sciences Laboratory  
NASA Goddard Space Flight Center  
Greenbelt, Maryland

Renata del Giudice Rodriguez  
CAPES Foundation  
Ministry of Education of Brazil, Brasilia,  
Distrito Federal, Brazil

A. Charles Rowney  
Longwood, Florida

Albert J. Ruguamu  
Makerere University  
College of Engineering, Design Art and Technology  
Department of Civil and Environmental Engineering  
Kampala, Uganda

Udeshika Sakkama  
Research Assistant at the Institute of Water Policy  
Lee Kuan Yew School of Public Policy  
National University of Singapore  
Singapore

Jose D. Salas  
Department of Civil and Environmental Engineering  
Colorado State University  
Fort Collins, Colorado

Samuel Sandoval-Solis  
University of California Davis  
Dept. LAWR  
Davis, California

Sankar Sarkar  
Physics and Applied Mathematics Unit  
Indian Statistical Institute  
Kolkata, India
Arup K. Sarma  
Department of Civil Engineering  
Indian Institute of Technology Guwahati  
Guwahati, India

Shinji Sato  
Department of Civil Engineering  
University of Tokyo  
Tokyo, Japan

John Schaeke  
Annapolis, Maryland

William A. Schaeffelberg  
CEWR-HEC  
Hydrologic Engineering Center  
Davis, California

Anton Schleiss  
Laboratoire de constructions hydrauliques (LCH)  
Ecolepolytechniquefédérale de Lausanne (EPFL)  
LCH - ENAC - EPFL  
Lausanne, Switzerland

Sergio E. Serrano  
Department of Civil and Environmental Engineering  
Temple University  
Philadelphia, Pennsylvania

Yury V. Shauko  
Candidate of Physics and Mathematics  
Scientific Researcher of the Institute of Computational Modelling of Siberian Branch of Russian Academy of Sciences, Krasnoyarsk

Ashish Sharma  
School of Civil and Environmental Engineering  
The University of New South Wales  
Sydney, Australia

Jack Sharp  
University of Texas  
Austin, Texas

Mohsen Sherif  
Civil and Environmental Engineering Department  
College of Engineering  
UAE University  
United Arab Emirates

Haiyun Shi  
State Key Laboratory of Hydroscience and Engineering  
Tínghua University  
Beijing, People's Republic of China

Joel S. Sholtz  
Department of Civil and Environmental Engineering  
Colorado State University  
Fort Collins, Colorado

Lucas Siegfried  
Santa Cruz, California

Vijay P. Singh  
Department of Biological and Agricultural Engineering & Zachry Department of Civil Engineering  
Texas A&M University  
College Station, Texas

Bellie Swakumar  
School of Civil and Environmental Engineering  
The University of New South Wales  
Sydney, Australia

Brian E. Skahill  
CEERD-HFH  
Coastal and Hydraulics Laboratory  
Vicksburg, Mississippi

Lambert K. Smedema  
Independent Irrigation/Drainage Consultant  
Arlem, The Netherlands

S. Sorourshian  
University of California  
Irvine, California

Jery R. Stedinger  
School of Civil and Environmental Engineering  
Cornell University  
Ithaca, New York

R. Subbaiah  
Department of Soil and Water Engineering  
College of Agricultural Engineering and Technology  
Junagadh Agricultural University  
Junagadh, India

Caroline A. Sullivan  
School of Environment, Science and Engineering  
Marine Ecology Research Centre  
Southern Cross University  
New South Wales, Australia

Go Sun  
Eastern Forest Environmental Threat Assessment Center  
Southern Research Station, USDA Forest Service  
Raleigh, North Carolina

Liquin Sun  
Department of Civil Engineering  
The University of Hong Kong  
Hong Kong, People's Republic of China

Öli G. B. Svínsson  
Landvörður (The National Power Company of Iceland)  
Reykiavík, Iceland

David G. Tarboton  
Department of Civil and Environmental Engineering  
Utah State University  
Logan, Utah

Ashish Thakor  
Darbhanga College of Engineering  
Darbhanga, India

Reed Thayer  
Center for Watershed Sciences  
University of California Davis, California

Mark Thyer  
School of Engineering  
University of Newcastle  
Callaghan, Australia

Ezio Todini  
Institute of Hydraulic Construction  
University of Bologna  
Bologna, Italy

Glenn Tootle  
The University of Alabama  
Department of Civil, Construction and Environmental Engineering (CCCEE)  
Tuscaloosa, Alabama

Cecilia Tortajada  
Third World Centre for Water Management  
Mexico

Shivam Tripathi  
Indian Institute of Technology Kanpur  
Kanpur, India

Frank Y.-C. Tsai  
Louisiana State University  
Department of Civil and Environmental Engineering  
Baton Rouge, Los Angeles

Raphael M. Tsikamanga  
Department of Natural Resources Management & CB-HYDRONET  
Faculty of Agronomic Sciences  
University of Kinshasa  
Kinshasa, Democratic Republic of the Congo

Yewou-Koung Tung  
Taiwan, People's Republic of China

Kambalad Tissupova  
Department of Water Resources Engineering  
Lund University  
Lund, Sweden
Julie A. Vano
Research Applications Laboratory
National Center for Atmospheric Research

Jennifer C. Veilleux
Oregon State University
Corvallis, Oregon

Daniele Veneziano
Department of Civil and Environmental Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts

R. Vignesh
Department of Civil Engineering
Indian Institute of Technology Bombay
Mumbai, India

Gabriele Villarini
IIHR-Hydroscience and Engineering
The University of Iowa
Civil and Environmental Engineering
Iowa City, Iowa

Richard M. Vogel
Department of Civil and Environmental Engineering
Tufts University
Medford, Massachusetts

Harold W. Wainwright
Earth Sciences Division
Lawrence Berkeley National Laboratory
Berkeley, California

Glenn Warner
Department of Natural Resources and the Environment
The University of Connecticut
Storrs, Connecticut

Wallace A. Wilson
ASFPFM Foundation

Fitsum M. Woldemeskel
School of Civil and Environmental Engineering
The University of New South Wales
Sydney, Australia

Aaron T. Wolf
Oregon State University
Corvallis, Oregon

Ming-xiu Woo
School of Geography and Earth Sciences
McMaster University
Hamilton, Canada

Ralph A. Wurbs
Zachry Department of Civil Engineering
Texas A&amp;M University
College Station, Texas

Yi Xiao
Department of Systems Design Engineering
University of Waterloo
Waterloo, Canada

David Yang
Tsinghua University
Beijing, People's Republic of China

Daqing Yang
National Hydrology Research Center
Environment Canada
Saskatoon, Canada

Xiaoli Yang
State Key Laboratory of Hydrology
Water Resources and Hydraulic Engineering
Hohai University
Nanjing, People's Republic of China

Soojung Yi
University of California
Davis, California

Peter C. Young
Systems and Control Group
Lancaster Environment Centre
Lancaster University
Lancaster, United Kingdom

S. Yu
Witze Moscow University
Moscow, Russia

Fei Yuan
State Key Laboratory of Hydrology
Water Resources and Hydraulic Engineering
Hohai University
Nanjing, People's Republic of China

Edith Zagona
Research Professor
Department of Civil, Architectural and Environmental Engineering
University of Colorado
Boulder, Colorado

Kaveh Zamani
Research Professor
Department of Civil, Environmental and Architectural Engineering
University of Colorado
Boulder, Colorado

Ilya Zaslavsky
Spatial Information Systems Laboratory
San Diego Supercomputer Center
University of California, San Diego
La Jolla, California

Qiang Zhang
Department of Water Resources and Environment
Sun Yat-sen University
Guangzhou, People's Republic of China

Lan Zhang
Assistant Professor
Department of Civil Engineering
University of Akron
Akron, Ohio

Igor S. Zonn
Engineering Scientific-Production Center for Water Economy Reclamation & Ecology
Moscow, Russia

Daqing Yang
National Hydrology Research Center
Environment Canada
Saskatoon, Canada

Xiaoli Yang
State Key Laboratory of Hydrology
Water Resources and Hydraulic Engineering
Hohai University
Nanjing, People's Republic of China

Soojung Yi
University of California
Davis, California

Peter C. Young
Systems and Control Group
Lancaster Environment Centre
Lancaster University
Lancaster, United Kingdom

S. Yu
Witze Moscow University
Moscow, Russia

Fei Yuan
State Key Laboratory of Hydrology
Water Resources and Hydraulic Engineering
Hohai University
Nanjing, People's Republic of China

Edith Zagona
Research Professor
Department of Civil, Architectural and Environmental Engineering
University of Colorado
Boulder, Colorado

Kaveh Zamani
Research Professor
Department of Civil, Environmental and Architectural Engineering
University of Colorado
Boulder, Colorado

Ilya Zaslavsky
Spatial Information Systems Laboratory
San Diego Supercomputer Center
University of California, San Diego
La Jolla, California

Qiang Zhang
Department of Water Resources and Environment
Sun Yat-sen University
Guangzhou, People's Republic of China

Lan Zhang
Assistant Professor
Department of Civil Engineering
University of Akron
Akron, Ohio

Igor S. Zonn
Engineering Scientific-Production Center for Water Economy Reclamation & Ecology
Moscow, Russia
International Advisory Board

Chair: Richard H. McCuen
Department of Civil & Environmental Engineering
University of Maryland
Maryland

Andras Bardossy
Lehrstuhl für Hydrologie und Geohydrologie
Institute für Wasser- und Umweltsystemmodellierung
Universität Stuttgart
Stuttgart, Germany

Ronny Berndtsson
Department of Water Resources Engineering & Center for Middle Eastern Studies
Lund University
Lund, Sweden

Corrado Corradini
Department of Civil and Environmental Engineering
University of Perugia
Perugia, Italy

James F. Cruise
Department of Civil and Environmental Engineering, University of Alabama
Huntsville, Alabama

João Pedroso de Lima
Department of Civil Engineering
University of Coimbra
Coimbra, Portugal

M. Fiorentino
Department of Environmental Engineering and Physics
University of Basilicata
Potenza, Italy

R. S. Govindaraju
Delon and Elizabeth Hampton Hall of Civil Engineering
Purdue University
West Lafayette, Indiana

Nilgun B. Harmançioğlu
Dokuz Eylül University
Water Resources Management
Research & Application Center (SUMER)
İzmir, Turkey

Sharad Kumar Jain
Water Resources Systems Division
National Institute of Hydrology
Roorkee, India

M. Levent Kavvas
Department of Civil and Environmental Engineering
University of California
Davis, California

Yev Kuchment
Laboratory of Hydrological Cycle
Water Problems Institute of the Russian Academy of Sciences,
Moscow, Russia

Venkat Laxmi
Department of Earth and Ocean Sciences
University of South Carolina
Columbia, South Carolina

Upmanu Lall
Department of Earth and Environmental Engineering and Department of Civil Engineering and Engineering Mechanics
Columbia Water Center
International Research Institute for Climate and Society
Columbia University
New York

P. E. O’Connell
School of Civil Engineering and Geosciences
Newcastle University
New Castle upon Tyne, United Kingdom

C. S. P. Ojha
Department of Civil Engineering
Indian Institute of Technology Roorkee
Roorkee, India

U. S. Pana
Department of Civil Engineering
Lakehead University
Ontario, Canada

Fernando Falco Pruski
Agricultural Engineering Department
Federal University of Viçosa
Viçosa, Minas Gerais State, Brazil

Liliang Ren
State Key Laboratory of Hydrology, Water Resources and Hydraulic Engineering
Hohai University
Nanjing, China

Dan Rosbjerg
Department of Environmental Engineering
Technical University of Denmark
Copenhagen, Denmark

Jose D. Salas
Department of Civil and Environmental Engineering
Colorado State University
Fort Collins, Colorado

Sergio E. Serrano
Department of Civil & Environmental Engineering
Temple University
Philadelphia, Pennsylvania

Ashish Sharma
School of Civil and Environmental Engineering
The University of New South Wales
Sydney, New South Wales, Australia

Bellie Sivakumar
School of Civil and Environmental Engineering
The University of New South Wales
Sydney, Australia

Witold Strupczewski
Water Resources Department
Institute of Geophysics
Polish Academy of Sciences
Warsaw, Poland

Ezio Todini
University of Bologna
Bologna, Italy

Dawen Yang
Department of Hydraulic Engineering
Tsinghua University
Beijing, China

Qiang Zhang
Department of Water Resources and Environment
Sun Yat-sen University
Guangzhou, China
Practitioner Advisory Board

Chair: R. D. Singh
National Institute of Hydrology
Roorkee
India

Aaron R. Byrd
Research Hydraulic Engineer & Branch Chief
Hydrologic Systems Branch
Coastal and Hydraulics Laboratory
Engineer Research Development Center
U.S. Army Corps of Engineers
Vicksburg, Mississippi

Anthony S. Donigian, Jr.
AQUA TERRA Consultants
Mountain View, California

Donald K. Frevert
Retired Hydraulic Engineer and Team Leader
Bureau of Reclamation
Denver, Colorado

Randall (Randy) W. Gentry
Argonne National Laboratory
Environmental Science Division
Argonne, Illinois

Mohamed M. Hantush
Research Hydrologist
National Risk Management Research Laboratory
U.S. Environmental Protection Agency
Cincinnati, Ohio

T. Moramarco
National Research Council, Institute for Hydrogeological Protection,
Perugia, Italy

John W. Mueller
State Conservation Engineer
USDA-NRCS
Temple, Texas

B. Mukhopadhyay
Richards, Texas

J. Obeysekara
Hydrologic & Environmental Systems Modeling
South Florida Water Management District