

Hydrology and Hydroclimatology

Principles and Applications

A comprehensive compilation of scientific and engineering topics, **Hydrology and Hydroclimatology: Principles and Applications** combines coverage of many new challenges and emerging issues missing from many other textbooks in this field. The authors take a systems approach to understanding and applying the principles of hydrology and hydroclimatology, considering interactions among different components of water cycle.

The book provides a fresh look at the fundamentals and new challenges in hydrologic and hydroclimatic systems and climate change. The authors underscore the importance of the underlying concepts due to the emergence of non-traditional data sets and new investigation techniques applied to an expanding array of water-related problems.

Highlights include:

- System's view of hydroclimatology and hydrology
- Basic principles of hydrologic cycles and their interactions with hydroclimatic system
- Watersheds at the holistic scale in hydrologic studies
- Deterministic and stochastic investigations in hydrology
- Emerging issues in large and non-traditional data sets and regionalizing data
- Climate change assessment and evaluation of its impacts on hydrologic cycle
- Simulation and modeling tools and techniques in hydrology
- Quantifying risks and uncertainty including hazard, vulnerability, and resiliency
- Dealing with extreme hydrologic events: floods and droughts

Examining topics through the lens of current engineering issues, the book provides clear understanding of the hydrologic systems and their interactions, time series analysis, long lead forecasting and simulation, drought and flood management as well as risk and uncertainty in hydrologic design. The combined coverage of surface and groundwater hydrology, as well as deterministic and stochastic aspects of water science and engineering, provides practical tools and techniques for handling pressing water issues that have been amplified in urban areas.



CRC Press

Taylor & Francis Group
an informa business

www.taylorandfrancisgroup.com

6000 Broken Sound Parkway, NW
Suite 300, Boca Raton, FL 33487
711 Third Avenue
New York, NY 10017
2 Park Square, Milton Park
Abingdon, Oxon OX14 4RN, UK

K14878

ISBN: 978-1-4665-1219-1

90000



9 781466 512191
www.crcpress.com

Contents

Preface.....	xix
Acknowledgments.....	xxi
Authors.....	xxiii

Chapter 1 Introduction	1
1.1 Introduction	1
1.2 Systems Approach	1
1.3 Hydrologic Cycle	2
1.3.1 Watersheds and Aquifers.....	2
1.3.2 Rivers and Reservoirs.....	3
1.4 Hydrologic Variability	3
1.5 Disposition of Energy and Matter	4
1.6 Representations and Statistical and Simulation Models.....	4
1.7 Extreme Values, Vulnerability, Risk, and Uncertainty	5
1.8 Water Availability.....	5
1.9 Water Sustainability	6
1.10 Tools and Techniques	8
1.11 People's Perception—Public Awareness	9
1.12 Integrated Water Cycle Management	10
1.13 Economics of Water	10
1.14 Water Supply vs. Water Demand.....	11
1.15 Clean Water Act	12
1.15.1 The Basis of State Water Laws in the United States	13
1.16 Overall Organization of this Book	14
References	15

Chapter 2 Hydroclimatic Systems.....	17
2.1 Introduction	17
2.2 General Systems' Characteristics.....	17
2.2.1 System Properties.....	19
2.3 Systems Modeling	22
2.3.1 Model Resolution	22
2.4 Earth System	23
2.5 Atmosphere.....	25
2.5.1 General Circulation of the Atmosphere	27
2.6 Lithosphere	29
2.6.1 Crustal System.....	30
2.7 Biosphere	30
2.8 The Hydrosphere	30
2.8.1 Hydrologic Systems.....	31
2.8.2 Hydrologic System and Modeling Approaches.....	31
2.8.3 Hydrologic Variables and Parameters	32
2.9 Hydrologic Cycle	33
2.9.1 The Movement of Water in the Earth–Atmosphere System	37

- 2.9.2 Evaporation and Transpiration 37
 - 2.9.3 Condensation 39
 - 2.9.4 Precipitation 40
 - 2.9.5 The Surface Water Balance 40
 - 2.9.6 The Atmospheric Water Balance 42
 - 2.9.7 Hydroclimatology 43
- 2.10 The Catchment Basin System 43
 - 2.10.1 Lake Catchment Systems 46
 - 2.10.2 The Fluvial System 46
 - 2.10.3 Energy and Mass Transfer in Channel Systems 48
- 2.11 Groundwater System 51
 - 2.11.1 Confined and Unconfined Aquifers 51
 - 2.11.2 Stream–Aquifer Interaction 53
- 2.12 Concluding Remarks 53
- References 55

Chapter 3 Hydroclimatic Processes 57

- 3.1 Introduction 57
- 3.2 Atmosphere Characteristics 57
- 3.3 Physical Behavior of the Atmosphere 58
 - 3.3.1 Ideal Gas Law 58
 - 3.3.1.1 Common Form 59
 - 3.3.1.2 Molar Form 60
 - 3.3.1.3 Isothermal and Adiabatic Expansion 61
 - 3.3.2 Atmospheric Pressure 61
 - 3.3.3 Atmospheric Temperature 61
 - 3.3.3.1 Global Energy Balance 64
- 3.4 Heat and Temperature Relationship 66
 - 3.4.1 Latent Heat 66
 - 3.4.2 Lapse Rate 67
 - 3.4.2.1 Dry Adiabatic Lapse Rate 68
 - 3.4.2.2 Saturated Adiabatic Lapse Rate 69
 - 3.4.3 Atmospheric Stability 70
 - 3.4.3.1 Temperature Inversions 72
- 3.5 Measures of Water Vapor in the Atmosphere 73
 - 3.5.1 Density of Moist Air 76
- 3.6 Clouds and Precipitation Formation 77
 - 3.6.1 Cloud Formation 78
 - 3.6.2 Hurricane Formation 79
- 3.7 Climate Variability 79
 - 3.7.1 El Niño, La Niña, and Southern Oscillation 80
 - 3.7.2 Sea Level Pressure 82
 - 3.7.3 Sea Surface Temperature 82
 - 3.7.4 Southern Oscillation Index 82
 - 3.7.5 The North Atlantic Oscillation 83
 - 3.7.6 Monsoon 84
- 3.8 Case Studies 85
 - 3.8.1 Case Study 1 85
 - 3.8.1.1 Data 85
 - 3.8.1.2 Results 86

- 3.8.2 Case Study 2.....87
 - 3.8.2.1 Study Area88
 - 3.8.2.2 Results of Large-Scale Signal Analysis.....88
- 3.9 Conclusion90
- References92

Chapter 4 Hydrologic Cycle Analysis93

- 4.1 Introduction93
- 4.2 Precipitation.....93
 - 4.2.1 Estimation of Missing Rainfall Data95
 - 4.2.2 Average Areal Rainfall.....96
 - 4.2.2.1 Station Average Method96
 - 4.2.2.2 Thiessen Method.....96
 - 4.2.2.3 Isohyetal Method98
 - 4.2.3 Snowmelt Estimation.....99
- 4.3 Evaporation and Evapotranspiration102
 - 4.3.1 Evaporation Evaluation103
 - 4.3.1.1 Water Budget Method103
 - 4.3.1.2 Mass Transfer Method103
 - 4.3.1.3 Pan Evaporation104
 - 4.3.2 Measurement of Evapotranspiration104
 - 4.3.2.1 Blaney–Criddle Method104
 - 4.3.2.2 Thornthwaite Method106
 - 4.3.2.3 Jensen–Haise Method107
- 4.4 Interception Storage and Depression Storage.....109
- 4.5 Infiltration.....110
 - 4.5.1 Green–Ampt Model110
 - 4.5.1.1 Ponding Time.....113
 - 4.5.2 Horton Method118
 - 4.5.3 Holtan Method.....120
- 4.6 Calculation of Excess Rainfall–Runoff.....121
- 4.7 Groundwater124
- 4.8 Reservoirs and Lakes125
- 4.9 Water Balance.....126
 - 4.9.1 Thomas Model (*abcd* Model).....127
- 4.10 Regionalizing the Hydrologic Data Using the Kriging Method.....129
 - 4.10.1 Theoretical Semivariogram Models130
 - 4.10.1.1 The Gaussian Semivariogram Model130
 - 4.10.1.2 The Exponential Semivariogram Model131
 - 4.10.1.3 The Spherical Semivariogram Model.....131
 - 4.10.1.4 The Sine Hole Effect Semivariogram Model131
 - 4.10.1.5 The Power Semivariogram Model.....131
 - 4.10.2 Kriging System.....132
 - 4.10.3 Fitting Variogram.....134
 - 4.10.4 Cross-Validation136
- 4.11 Summary137
- References141

Chapter 5	Watersheds	143
5.1	Definition.....	143
5.2	Watershed Geomorphology	143
5.2.1	Drainage Area	143
5.2.2	Basin Length	143
5.2.3	Basin Slope.....	144
5.2.4	Basin Shape	145
5.2.5	Length to the Center of Area (<i>LC</i>).....	150
5.2.6	Equivalent Rectangular	150
5.2.7	Drainage Density.....	151
5.2.7.1	Horton's Laws	151
5.3	Hypsometric Curve.....	157
5.4	Characteristics of Soil	162
5.4.1	Texture of Soil.....	162
5.4.2	Soil Structure.....	162
5.4.3	Soil Moisture	163
5.5	Channel Geomorphology	163
5.5.1	Length of a Channel	163
5.5.2	Slope of a Channel	165
5.5.2.1	Method 1	166
5.5.2.2	Method 2.....	167
5.5.2.3	Method 3.....	167
5.5.2.4	Method 4.....	167
5.5.2.5	Method 5.....	167
5.5.2.6	Method 6.....	167
5.5.2.7	Method 7.....	168
5.5.3	Law of Stream Slopes.....	171
5.5.4	Channel Cross Section	172
5.5.5	Channel Roughness	172
5.6	Travel Time.....	175
5.6.1	Definitions of Time of Concentration	175
5.6.2	Classifying Time Parameters	176
5.6.3	Velocity Method	178
5.6.4	Sheet Flow Travel Time	179
5.6.5	Empirical Formulas.....	186
5.6.5.1	The Carter Lag Equation for Partially Sewered Watersheds.....	186
5.6.5.2	The Eagleson Lag Model.....	187
5.6.5.3	The Espey–Winslow Equation.....	187
5.6.5.4	Federal Aviation Agency (FAA) Equation	187
5.6.5.5	Kerby–Hathaway Formula.....	187
5.6.5.6	Kirpich's Methods	188
5.6.5.7	The SCS Lag Formula	188
5.6.5.8	The Van Sickle Equation	188
5.7	Land Use and Cover Impacts	189
5.7.1	Forest Areas	189
5.7.2	Urban Areas	191
5.7.3	Wetland Areas	192
5.8	Concluding Remarks	192
	References	195

Chapter 6 Surface Water Hydrology 197

6.1 Introduction 197

6.2 Estimation of Runoff Volume..... 198

6.2.1 SCS Method 198

6.2.2 Rational Method..... 203

6.2.2.1 IDF Curves 204

6.2.3 Coefficient and Regression Methods..... 209

6.3 Hydrograph Theory 209

6.4 Baseflow Estimation 210

6.4.1 Constant-Discharge Baseflow..... 211

6.4.2 Constant-Slope Baseflow..... 212

6.4.3 Concave Baseflow..... 213

6.4.4 Master Depletion Curve Method..... 214

6.5 Unit Hydrograph..... 215

6.5.1 Definitions 215

6.5.2 Limitations of Unit Hydrograph..... 216

6.5.3 Convolution 218

6.5.4 Least-Squares Analysis of Unit Hydrographs 224

6.6 Different Types of Unit Hydrographs..... 225

6.6.1 SCS Unit Hydrograph..... 225

6.6.2 Espey 10 min Unit Hydrograph..... 229

6.6.3 Snyder’s Synthetic Unit Hydrograph..... 233

6.7 Unit Hydrograph Adjustments..... 237

6.7.1 S-Hydrograph Method..... 239

6.7.2 Gamma Function Unit Hydrograph..... 246

6.7.3 Averaging Storm Event Unit Hydrographs..... 247

6.7.4 Dimensionless Unit Hydrographs..... 248

6.8 Instantaneous Unit Hydrographs..... 248

6.8.1 Nash Model 251

6.8.2 Laplace Transformation Model 257

6.8.2.1 Basin as a Linear Reservoir..... 257

6.8.2.2 Basin as a Channel..... 261

6.8.3 Time–Area Unit Hydrographs..... 262

6.9 Routing Methods 269

6.9.1 Hydrologic Methods of River Routing 269

6.9.1.1 Muskingum Method 270

6.9.1.2 Determination of Storage Constants..... 273

6.9.1.3 Muskingum–Cunge Method..... 274

6.10 Hydrologic Reservoir Routing..... 278

6.10.1 Storage Indication Method 278

6.10.2 Detention Basin Routing 280

6.11 Estuaries 284

6.12 Water Quality Issues in Surface Water..... 285

6.12.1 Physical Parameters..... 286

6.12.1.1 Temperature 286

6.12.1.2 Salinity..... 286

6.12.1.3 Suspended Material Concentration and Turbidity 286

6.12.1.4 Current Speed and Direction..... 287

6.12.1.5 Meteorological Parameters (Weather)..... 287

6.12.2 Chemical Parameters 287

6.12.2.1 Oxygen 287

6.12.2.2 Nutrients 287

6.12.2.3 pH and Alkalinity 288

6.12.2.4 Chlorophyll a 288

6.12.2.5 Toxic Contaminants 288

6.12.3 Biological Parameters..... 288

6.12.3.1 Pathogens (Indicator Bacteria)..... 288

6.12.4 Oxygen Sag Model 289

Appendix 296

References 299

Chapter 7 Groundwater Hydrology..... 301

7.1 Introduction 301

7.2 Groundwater Systems..... 302

7.3 Groundwater Availability 303

7.4 Groundwater Development..... 304

7.5 Types of Aquifers 305

7.5.1 Unconfined Aquifer 305

7.5.2 Confined Aquifers 306

7.5.3 Aquitard (Leaky) Aquifer 306

7.6 Aquifer Characteristics..... 306

7.6.1 Porosity and Void Ratio..... 306

7.6.2 Specific Yield in Unconfined Aquifers 309

7.6.3 Specific Retention..... 309

7.6.4 Storage Coefficient and Specific Storage 311

7.6.5 Safe Yield of Aquifers 314

7.7 Groundwater Balance 315

7.7.1 Water Balance in Confined Aquifers 316

7.7.2 Water Balance in Unconfined Aquifers..... 316

7.7.3 Water Balance in Unsaturated Zone 317

7.8 Groundwater Movement 317

7.8.1 Darcy’s Law..... 317

7.8.2 Hydraulic Head..... 319

7.8.3 Hydraulic Conductivity 320

7.8.3.1 Hydraulic Conductivity in Saturated Media..... 320

7.9 Homogeneous and Isotropic Systems 322

7.9.1 Hydraulic Conductivity in Multilayer Structures..... 323

7.10 Transmissivity 324

7.11 Dupuit–Forchheimer Theory of Free-Surface Flow 325

7.12 Flownets 327

7.12.1 Isotropic and Homogeneous Media..... 327

7.12.2 Heterogeneous Media..... 331

7.12.3 Anisotropic Media..... 332

7.13 Wells 333

7.13.1 Steady Flow into a Well 335

7.13.1.1 Confined Flow 335

7.13.1.2 *Unconfined Flow* 336

7.13.2 Unsteady State in a Confined Aquifer..... 337

7.13.2.1 Aquifer Test Application..... 341

7.13.2.2	Theis Method of Solution	341
7.13.2.3	Cooper–Jacob Method-Modified Theis	343
7.13.3	Unsteady State for Unconfined Aquifer	345
7.14	Multiple-Well Systems	348
7.15	Effective Conditions on Time-Drawdown Data	349
7.15.1	Recharge Boundary	349
7.15.2	Impermeable Boundary	351
7.15.3	Partially Penetrating Wells	352
7.16	Interaction between Surface and Groundwater	354
7.16.1	Infiltration	354
7.16.2	Concepts of Interaction between Surface Water and Groundwater	355
7.16.3	Bank Storage and Baseflow Recession	356
7.16.4	Groundwater and Lakes	356
7.17	Concluding Remarks	357
	References	360

Chapter 8	Time Series Analysis	363
8.1	Introduction	363
8.2	Stochastic Processes	364
8.3	Time Series	365
8.4	Hydrological Time Series	366
8.4.1	Rainfall	367
8.4.2	Runoff	368
8.5	Hydrologic Time Series Modeling: Basic Steps	369
8.6	Data Preparation	370
8.6.1	Removing Data Trend	370
8.6.2	Jump	373
8.6.3	Periodicity (Seasonality)	373
8.6.4	Time Series Memory	374
8.6.4.1	Hurst Coefficient	374
8.6.5	Data Normalization	375
8.6.6	Time Dependency	378
8.7	Time Series Modeling in Hydrology	380
8.8	Methods of Parameter Estimation	381
8.8.1	Method of Moments	381
8.8.2	Method of Least Squares	382
8.8.3	Method of Maximum Likelihood	384
8.9	Regression-Based Methods	386
8.9.1	ARMA(p, q) Model Identification	386
8.9.1.1	Autocorrelation Function	386
8.9.1.2	Partial Autocorrelation Function (PACF)	386
8.9.2	Autoregressive (AR) Models	388
8.9.3	Moving Average Process	392
8.9.4	Autoregressive Moving Average Modeling	393
8.9.4.1	Generation and Forecasting Using ARMA Models	397
8.9.5	Akaike's Information Criterion (AIC)	397
8.9.5.1	Generation and Forecasting	398
8.9.6	Autoregressive Integrated Moving Average Modeling	399
8.9.6.1	Time Series Forecasting Using ARIMA Models	400

8.9.7	Autoregressive–Moving Average Model with Exogenous Inputs (ARMAX) Model.....	404
8.9.8	Multivariate and Disaggregation Modeling of Time Series.....	404
8.10	Goodness-of-Fit Tests.....	410
8.10.1	Chi-Square Goodness-of-Fit Test.....	411
8.10.2	Kolmogorov–Smirnov Goodness-of-Fit Test.....	413
8.10.3	The Portmanteau Test.....	414
8.10.4	The Cumulative Periodogram Test.....	416
8.11	Spectral-Analysis-Based Methods.....	416
8.11.1	Spectral Analysis Primer.....	416
8.11.2	Periodogram.....	417
8.11.3	Frequency Interpretation.....	417
8.11.4	Spectral Density Function.....	420
8.11.5	ANOVA Decomposition.....	420
8.11.6	Spectral Density and ARMA Model.....	422
8.11.7	GARCH Model.....	422
8.12	Concluding Remarks.....	424
	Appendix.....	427
	References.....	431
Chapter 9	Climate Change Impacts and Models.....	433
9.1	Introduction.....	433
9.2	The Greenhouse Effect.....	433
9.2.1	The Principle of Greenhouse Gas Effects.....	434
9.2.2	Atmospheric Concentration of CO ₂	434
9.3	Carbon Cycle.....	435
9.3.1	Estimating Carbon Emission: The Kaya Identity.....	437
9.4	Climate Change Impact on Hydrologic Cycle.....	439
9.5	Water Resource System Effects.....	441
9.5.1	Floods and Droughts.....	441
9.5.2	Agricultural Droughts.....	442
9.5.3	Water Use.....	442
9.5.4	Water Quality.....	442
9.5.5	Habitat.....	442
9.5.6	Hydroelectric Power.....	443
9.5.7	Snowpack.....	443
9.5.8	Riverflow.....	443
9.6	Climate Change Simulation.....	443
9.6.1	Climate Change Scenarios.....	444
9.6.1.1	Spatial Variability.....	444
9.6.2	Downscaling.....	446
9.6.2.1	Statistical Downscaling Model.....	449
9.6.2.2	Stochastic Weather Generator Model (LARS-WG).....	452
9.7	Case Studies.....	455
9.7.1	Case Study 1: Assessment of Climate Change Impacts on Hydroclimatic Variables in the Aharchai River Basin.....	455
9.7.1.1	Study Area.....	455
9.7.1.2	Methodology and Results.....	455
9.7.2	Case Study 2: Evaluation of Climate Change Impacts on Urban Floods.....	457

9.7.2.1	Study Area	457
9.7.2.2	Methodology	458
9.7.2.3	Results.....	461
9.7.3	Case Study 3: Impacts on Future Droughts.....	463
9.7.4	Case Study 4: Evaluation of Climate Change Impacts on Irrigation Water Demand	463
References		469

Chapter 10 Probability, Risk, and Uncertainty in Hydrologic Analysis..... 471

10.1	Introduction	471
10.2	Probability Treatment of Hydrologic Data	471
10.2.1	Discrete and Continuous Random Variables.....	473
10.2.2	Moments of Distribution	473
10.3	Common Probabilistic Models	478
10.3.1	The Binomial Distribution	478
10.3.2	Normal Distribution	479
10.3.3	Lognormal Distribution.....	480
10.3.4	The Exponential Distribution.....	481
10.3.5	The Gamma (Pearson Type 3) Distribution	481
10.3.6	The Log Pearson Type 3 Distribution	482
10.4	Return Period or Recurrence Interval	482
10.5	Reliability	483
10.5.1	Reliability Analysis Load-Resistance Concept.....	488
10.5.2	Direct Integration Method.....	490
10.5.3	Margin of Safety	491
10.5.4	Factor of Safety	492
10.5.5	Multivariate Reliability Analysis	492
10.5.5.1	Copula Theory	494
10.6	Risk.....	495
10.6.1	Risk Components	497
10.6.2	Risk Analysis Methods and Tools	499
10.6.2.1	Environmental Risk Analysis.....	500
10.6.3	Risk Management.....	502
10.7	Vulnerability.....	503
10.7.1	Vulnerability Estimation	503
10.7.1.1	Vulnerability Software	506
10.7.2	Risk Reduction through Reducing Vulnerability.....	507
10.8	Resiliency	508
10.9	Uncertainty	509
10.9.1	Implications of Uncertainty	512
10.9.2	Uncertainty of Hydrological Forecasting.....	513
10.9.3	Measures of Uncertainty	513
10.9.3.1	Entropy Theory.....	514
10.9.3.2	Probability Theory—Bayes’ Theorem	516
10.9.3.3	Fuzzy Set Theory.....	517
10.9.4	Analysis of Uncertainty.....	518
10.9.4.1	Mean Value First-Order Second-Moment Method.....	519
Appendix		523
References		526

Chapter 11	Hydrologic Simulation.....	529
11.1	Introduction	529
11.2	Mathematical Simulation Techniques	529
11.2.1	Stochastic Simulation	530
11.2.2	Stochastic Processes.....	530
11.2.3	Markov Processes and Markov Chains.....	532
11.2.4	Monte Carlo Technique.....	535
11.2.5	Artificial Neural Networks.....	538
11.2.5.1	Multilayer Perceptron Network (Static Network)	541
11.2.5.2	Recurrent Neural Network.....	543
11.2.5.3	Input-Delayed Neural Network.....	544
11.2.5.4	Time Delay Neural Network.....	545
11.2.5.5	General Regression Neural Network	548
11.2.5.6	Probabilistic Neural Network	550
11.2.6	<i>k</i> -Nearest Neighbor Algorithm.....	550
11.2.7	Fuzzy Sets and Parameter Imprecision	553
11.2.8	Fuzzy Inference System	556
11.2.8.1	Mamdani's Method.....	557
11.2.8.2	Sugeno's Method.....	560
11.2.9	Adaptive Neuro-Fuzzy Inference System	560
11.3	Physical Models' Simulation	567
11.3.1	Lumped Hydrological Models.....	568
11.3.2	IHACRES.....	568
11.3.3	Semi-Distributed Hydrological Models	570
11.3.3.1	HEC-HMS	570
11.3.3.2	StormNET	577
11.3.3.3	HBV	585
11.3.4	Model Structure.....	585
11.3.5	Distributed Hydrological Models	589
11.3.5.1	Watershed Modeling System	590
	References	597
Chapter 12	Drought Analysis and Management.....	599
12.1	Introduction	599
12.2	Drought as a Hazard.....	599
12.3	Drought Definition.....	600
12.4	Climatic Drought.....	602
12.4.1	Point Evaluation	602
12.4.1.1	Fitting Statistical Distribution	602
12.4.1.2	Analysis of Moving Averages.....	604
12.4.1.3	Point Evaluation of Drought Events in a Monthly Scale ..	606
12.4.1.4	Effective Rainfall and Rainfall Difference Series.....	606
12.4.1.5	Onset and Termination of Drought.....	609
12.4.2	Regional Analysis of Climatic Drought	614
12.4.2.1	Weighting Method	614
12.4.2.2	Median of Ratios Method	615
12.4.2.3	Combined Method	616
12.4.3	Climatic Drought Indicators.....	617
12.4.3.1	Standard Precipitation Index	617

12.5 Hydrological Drought..... 619

12.5.1 Reservoir Operation and Demand Allocation..... 620

12.5.2 Hydrological Drought Indices: SWSI..... 620

12.6 Agricultural Drought..... 621

12.6.1 Agricultural Drought Indicators..... 621

12.6.1.1 Thornthwaite Water Balance Model..... 622

12.6.1.2 Potential Evapotranspiration..... 622

12.6.1.3 Soil Moisture Condition 622

12.6.1.4 Runoff Calculation..... 623

12.6.1.5 Potential Climatic Values 624

12.6.1.6 Coefficients of Water Balance Parameters 624

12.6.1.7 Climatically Appropriate for Existing Condition ($\hat{P}$)..... 625

12.6.1.8 Moisture Anomaly Index (Z)..... 626

12.6.1.9 Climatic Character, k 626

12.6.1.10 Palmer Drought Severity Index 627

12.6.1.11 Crop Moisture Index..... 629

12.6.2 Sequence of Drought Impacts 629

12.6.3 Economic Aspects of Water Shortage..... 630

12.7 Hybrid Drought Index 634

12.7.1 Evaluation of Water Availability and Drought Damage 637

12.7.2 A Case Study..... 639

12.8 Geostatistic Tools in Drought Studies 641

12.8.1 Spatial Kriging in Drought Studies..... 641

12.8.2 Spatial–Temporal Kriging..... 642

12.9 Drought Preparedness/Management 643

12.9.1 Drought Monitoring as a Component of Drought Preparedness Planning 644

12.9.1.1 Principles of Drought Policy..... 644

12.9.1.2 Drought Mitigation Planning..... 644

References 649

Chapter 13 Flood..... 651

13.1 Introduction 651

13.2 Flood Types 652

13.2.1 Flash Floods 652

13.2.2 Coastal Floods..... 652

13.2.3 Urban Floods 653

13.2.4 River Floods 653

13.2.5 Ponding or Pluvial Flooding 654

13.2.6 Inland and Coastal Flooding..... 654

13.2.6.1 Inland Flooding 654

13.2.6.2 Coastal Flooding..... 655

13.3 Flood Analysis..... 658

13.3.1 Flood Time Series 658

13.3.1.1 Peaks over Threshold Series..... 658

13.3.2 Flood Probability Analysis..... 659

13.3.3 Testing for Quilters..... 666

13.4 Flood Prediction 668

13.5 Flood Routing..... 669

13.5.1 Simple Non-Storage Routing..... 670

13.5.2	Storage-Based Routing	672
13.6	Urban Floods	672
13.6.1	Urban Flood Control Principles	672
13.7	Understanding Flood Hazards	673
13.7.1	Climate Change and Flooding	673
13.7.2	Sea Level Rise and Storm Surge	674
13.8	Evacuation Zones	674
13.9	Flood Damage	676
13.9.1	Stage–Damage Curve	677
13.9.2	Expected Damage	678
13.10	Flood Risk Management	680
13.10.1	Resiliency and Flood Risk Management	682
13.11	Floodplain Management	682
13.11.1	Structural Measures in Flood Management	683
13.11.2	The Role of Nonstructural Measures	684
13.11.3	BMPs and Flood Control	684
13.11.4	Watershed Flood Early Warning System	685
13.11.5	Flood Insurance	687
13.12	Case Studies	688
13.12.1	Case Study 1: Probabilistic Optimization Model for Floodplain Management	688
13.12.2	Case Study 2: Improvement of Urban Drainage System Performance under Climate Change Impact	689
13.12.3	Case Study 3: Evaluation of Floodplain Variability Considering Climate Change Impacts	692
13.12.4	Case Study 4: Optimal Flood Management Options with Probabilistic Optimization	695
13.12.5	Case Study 5: Evaluation of Climate Change Impact on Regional Flood Characteristics	698
	References	702
	Index	705