# **Contents**

#### Preface

1	Introduction to Hydrologic Science					
	1.1	Definit	ion and Scope of Hydrology 1			
	1.2	Development of Scientific Hydrology 1				
	1.3	.3 Approach and Scope of This Book 5				
2	Basi	c Hydro	ologic Concepts	7		
	2.1	Physical Quantities and Laws 7				
	2.2	Hydrologic Systems 7				
	2.3	The Conservation Equations 8				
	2.4	The Watershed (Drainage Basin) 10				
		2.4.1 2.4.2	Definition 10 Delineation 10			
	2.5	The Regional Water Balance 11				
		2.5.1 2.5.2				
	2.6	Spatial Variability 17				
	2.7	•				
		2.7.1 2.7.2				
	2.8	Storage, Storage Effects, and Residence Time 22				
		2.8.1 2.8.2 2.8.3	Storage Effects 23			
	2.9	Hydrologic Modeling 25				
		2.9.1	What is a Model? 25			

2.9.2

2.9.3

Purposes of Models 26

Types of Models 27

- 2.9.4 The Modeling Process 27
- 2.9.5 The BROOK90 Model 32
- Final Words of Caution 33 2.9.6

ix

3

#### Climate, the Hydrologic Cycle, Soils, and **Vegetation: A Global Overview** 36

#### 3.1 Basic Aspects of Global Climate 36

- The Energy Budget of the Earth 36 3.1.1
- Latitudinal Energy Transfer 39 3.1.2
- The General Circulation and 3.1.3 the Distribution of Pressure and Temperature 41
- 3.1.4 Teleconnections: El Niño and the Southern Oscillation 44

#### 3.2 The Global Hydrologic Cycle 48

- 3.2.1 Stocks and Fluxes in the Global Cycle 48
- Distribution of Precipitation 49 3.2.2
- Distribution of Evapotranspiration 55 3.2.3
- 3.2.4 Distribution of Runoff 61
- Continental Water Balances 64 3.2.5
- 3.2.6 Major Rivers and Lakes 64
- Material Transport by Rivers 64 3.2.7
- 3.2.8 Your Role in the Global Hydrologic Cycle 72
- 3.2.9 Climate Change and the Hydrologic Cycle 73

#### Climate, Soils, and Vegetation 83 3.3

- 3.3.1 Climate and Soils 83
- 3.3.2 Climate and Vegetation 89

94

#### 4 Precipitation

#### 4.1 Meteorology of Precipitation 94

- Uplift Due to Convergence 95 4.1.1
- 4.1.2 Uplift Due to Convection 98
- iİİ

- 4.1.3 Uplift Due to Orography 98
- 4.1.4 Critical Temperature for Rain-Snow Transition 103
- 4.1.5 Moisture Sources and Precipitation Recycling 104

#### 4.2 Measurement at a Point 105

- 4.2.1 Types of Precipitation Gages 105
- 4.2.2 Factors Affecting Measurement Accuracy 108
- 4.2.3 Estimating Missing Data 115
- 4.2.4 Checking the Consistency of Point Measurements 117

#### 4.3 Areal Estimation 118

- 4.3.1 Direct Weighted Averages 119
- 4.3.2 Surface-Fitting Methods 121
- 4.3.3 Comparison of Methods and Summary 127
- 4.3.4 Precipitation-Gage Networks 130
- 4.3.5 Radar and Satellite Observation 135

#### 4.4 Precipitation and Rainfall Climatology 140

- 4.4.1 Long-Term Average Precipitation Rates 140
- 4.4.2 Seasonal Variability of Precipitation 140
- 4.4.3 Storm Climatology 145
- 4.4.4 Extreme Rainfall Amounts 146
- 4.4.5 Anthropogenic Effects on Precipitation Climatology 160

#### 4.5 Precipitation Quality 162

## 5

#### Snow and Snowmelt

166

- 5.1 Material Characteristics of Snow 166
  - 5.1.1 Snow Properties 166
  - 5.1.2 Snowpack Metamorphism 167

#### 5.2 Measurement of Snow and Snowmelt 168

- 5.2.1 Precipitation 169
- 5.2.2 Snowfall 173
- 5.2.3 Snowpack 173
- 5.2.4 Snowmelt, Ablation, and Water Output 178
- 5.3 Hydrologic Importance and Distribution of Snow 179
  - 5.3.1 Water Input 179
  - 5.3.2 Distribution of Snow 179
- 5.4 Snowmelt Processes 185
  - 5.4.1 Phases of Snowmelt 185

- 5.4.2 The Energy Balance 190
- 5.4.3 Movement of Water through Snow 204
  - unough Show 20

#### 5.5 Snowmelt Modeling 207

- 5.5.1 Snowmelt at a Point 207
- 5.5.2 Watershed Snowmelt Modeling 214
- 5.6 Water-Quality Aspects 215

#### Water in Soils: Infiltration and Redistribution

6

#### 220

#### 6.1 Material Properties of Soil 221

- 6.1.1 Distribution of Pores
  - and Particle Sizes 221
- 6.1.2 Particle Density 222
- 6.1.3 Bulk Density 222
- 6.1.4 Porosity 222

#### 6.2 Soil-Water Storage 224

- 6.2.1 Volumetric Water Content 224
- 6.2.2 Degree of Saturation 226
- 6.2.3 Total Soil-Water Storage 227

#### 6.3 Soil-Water Flow 227

- 6.3.1 Darcy's Law 227
- 6.3.2 Soil-Water Pressure 228
- 6.3.3 Pressure–Water-Content Relations 230
- 6.3.4 Hydraulic Conductivity 231
- 6.3.5 Hydraulic-Conductivity-
  - Water-Content Relations 231
- 6.3.6 Analytic Approximations of  $\psi \theta$  and  $K_h \theta$  Relations 232
- 6.3.7 Hydraulic Diffusivity 234
- 6.3.8 Sorptivity 235

#### 6.4 Water Conditions in Natural Soils 235

- 6.4.1 Soil-Water Status 235
- 6.4.2 Soil Profiles 238

#### 6.5 Infiltration: Measurement and Qualitative Description 243

- 6.5.1 Definitions 243
- 6.5.2 Measurement 243
- 6.5.3 Basic Characteristics of the Infiltration Process 245
- 6.5.4 Factors Affecting Infiltration Rate 246
- 6.6 Quantitative Modeling of Infiltration at a Point 248
  - 6.6.1 The Richards Equation 249

- 6.6.2 The Green-and-Ampt Model 251
- 6.6.3 Green-and-Ampt Approach for Shallow Soils 258
- 6.6.4 Application of the Philip Equation 261
- 6.6.5 Infiltration over Areas 261

#### 6.7 Redistribution 265

- 6.7.1 Completely Wetted Profiles 266
- 6.7.2 Partially Wetted Profiles 267
- 6.7.3 Modeling 268
- 6.8 Summary 269

#### Evapotranspiration

### 272

8

- 7.1 Physics of Evaporation and Turbulent Energy Exchange 273
  - 7.1.1 Evaporation 273
  - 7.1.2 Vapor-Pressure Relations 273
  - 7.1.3 Latent-Heat Exchange 274
  - 7.1.4 Sensible-Heat Exchange 274
  - 7.1.5 The Bowen Ratio, the Psychrometric Constant, and the Evaporative Fraction 274
  - 7.1.6 The Energy Balance 274

#### 7.2 Classification of Evapotranspiration Processes 275

#### 7.3 Free-Water, Lake, and Wetland Evaporation 275

- 7.3.1 Water-Balance Approach 276
- 7.3.2 Mass-Transfer Approach 277
- 7.3.3 Eddy-Correlation Approach 280
- 7.3.4 Energy-Balance Approach 281
- 7.3.5 Penman or Combination Approach 285
- 7.3.6 Pan-Evaporation Approach 288

#### 7.4 Bare-Soil Evaporation 291

- 7.5 Transpiration 294
  - 7.5.1 The Transpiration Process 294
  - 7.5.2 Modeling Transpiration 295

#### 7.6 Interception and Interception Loss 301

- 7.6.1 Definitions 302
- 7.6.2 Measurement 302
- 7.6.3 Modeling 303
- 7.6.4 Hydrologic Importance of Interception Loss 306
- 7.6.5 Water-Quality Aspects 308

#### 7.7 Potential Evapotranspiration 308

7.7.1 Conceptual Definition 308

- 7.7.2 Operational Definitions 310
- 7.7.3 Comparison of PET
  - Estimation Methods 311

#### 7.8 Actual Evapotranspiration 311

- 7.8.1 Potential-Evapotranspiration Approaches 311
- 7.8.2 Water-Balance Approaches 318
- 7.8.3 Turbulent-Transfer/Energy-Balance Methods 321
- 7.8.4 Methods Based on Water-Quality Analyses 322

### Ground Water in the Hydrologic Cycle

#### 325

#### 8.1 Basic Principles of Ground-Water Flow 326

- 8.1.1 Darcy's Law 326
- 8.1.2 Classification of Ground-Water Flows 327
- 8.1.3 Storage Properties of Porous Media 328
- 8.1.4 Transmission Properties of Porous Media 331
- 8.1.5 Response Characteristics of Porous Media 332
- 8.1.6 General Ground-Water Flow Equation 333

#### 8.2 Regional Ground-Water Flow 335

- 8.2.1 General Features 337
- 8.2.2 Effects of Topography 337
- 8.2.3 Effects of Geology 338

#### 8.3 Ground-Water—Surface-Water Relations 342

- 8.3.1 Ground Water and Streams 342
- 8.3.2 Ground Water and Lakes and Wetlands 347
- 8.3.3 Ground Water and the Ocean 350

#### 8.4 Ground Water in the Regional Water Balance 354

- 8.4.1 Basic Water-Balance Relations 354
- 8.4.2 Ground-Water Residence Time 354
- 8.4.3 The Dupuit Approximation for Modeling Flow in Unconfined Aquifers 356
- 8.5 Evaluation of Ground-Water-Balance Components 358
  - 8.5.1 Recharge from Infiltration 358
  - 8.5.2 Recharge from Surface Water 370
  - 8.5.3 Ground-Water Contributions to Streamflow 371

g

- 8.5.4 Capillary Rise 376
- 8.5.5 Deep Seepage 377

#### 8.6 Impacts of Ground-Water Development on Basin Hydrology 379

- 8.6.1 Hydraulics of Ground-Water Development 379
- 8.6.2 Effects of Ground-Water Extraction 382
- 8.6.3 "Safe Yield" 387
- Stream Response to Water-Input Events

#### 9.1 Basic Aspects of Stream Response 389

389

- 9.1.1 The Phenomenon of Stream Response. 389
- 9.1.2 Hydrograph Separation 393
- 9.1.3 Event-Flow Volume 396
- 9.1.4 Quantitative Description of Response Hydrographs 396
- 9.1.5 Effects of Input and Basin Characteristics on the Hydrograph 402

#### 9.2 Mechanisms Producing Event Response 407

- 9.2.1 Channel Precipitation 407
- 9.2.2 Overland Flow 408
- 9.2.3 Subsurface Event Flow 412
- 9.2.4 Overview of Event-Response Mechanisms 424

#### 9.3 Open-Channel Flow and Streamflow Routing 424

- 9.3.1 Basic Relations of Open-Channel Flow 425
- 9.3.2 The Convex Routing Method 427

#### 9.4 The Stream Network 432

- 9.4.1 Quantitative Description of Stream Networks 432
- 9.4.2 Drainage Density 433
- 9.4.3 Relations between Network Characteristics and Stream Response 433

#### 9.5 Rainfall-Runoff Modeling 435

- 9.5.1 Basic Approach: The Systems View 436
- 9.5.2 Fundamental Considerations 438

#### 9.6 Rainfall-Runoff Models 443

9.6.1 The Rational Method 443

- 9.6.2 SCS Curve-Number Method 445
- 9.6.3 The Unit Hydrograph 450

## **10** Hydrology and Water-Resource Management

#### 10.1 Water-Resource Management 457

10.1.1 Water-Resource Management Goals and Objectives 457

457

- 10.1.2 The Geographical Unit for Water-Resources Management 460
- 10.1.3 The Management Process 461
- 10.1.4 The Role of Hydrologic Analysis 463

#### 10.2 Hydrologic Analysis: Water Supply and Demand 464

- 10.2.1 Classification of Water Uses 464
- 10.2.2 Water Use, Demand, and Shortage 464
- 10.2.3 Water Supply and "Safe Yield": Basic Concepts 465
- 10.2.4 Water Supply and "Safe Yield": Ground Water 466
- 10.2.5 Water Supply and "Safe Yield": Surface Water 472

#### 10.3 Hydrologic Analysis: Water Quality 488

- 10.3.1 Definitions and Basic Concepts 488
- 10.3.2 Overview of Major Water-Quality Issues 492
- 10.3.3 Examples of Hydrologic Analysis 494

#### 10.4 Hydrologic Analysis: Floods 500

- 10.4.1 Definitions and Basic Concepts 500
- 10.4.2 Overview of Major Flood Issues 501
- 10.4.3 Framework for Analysis of Floodplain-Management Alternatives 501
- 10.4.4 Flood-Frequency Analysis 506

#### 10.5 Hydrologic Analysis: Low Streamflows and Droughts 508

- 10.5.1 Definitions and Basic Concepts 508
- 10.5.2 Overview of Major Low-Flow and Drought Issues 510
- 10.5.3 Low-Flow Frequency Analysis 511
- 10.5.4 Drought Analysis 512
- 10.5.5 Concluding Comment 519

#### 10.6 Current and Projected Water Use 519

- 10.6.1 Basic Concepts 519
- 10.6.2 Current and Projected Use: United States 520
- 10.6.3 Current and Projected Use: Global 523

### Hydrologic Quantities

A

R

529

- A.1 Dimensions and Units 529
  - A.1.1 Dimensions 529
  - A.1.2 Units 530

#### A.2 Precision and Significant Figures 530

- A.2.1 Absolute Precision 530
- A.2.2 Relative Precision 531
- A.3 Unit Conversion 531

#### A.4 Equations: Dimensional Properties and Conversion 533

- A.4.1 Dimensional Properties 533
- A.4.2 Equation Conversion 534

## Water as a Substance

536

#### B.1 Structure of Water 536

- B.1.1 Molecular and Inter-Molecular Structure 536
- B.1.2 Freezing and Melting 537
- B.1.3 Evaporation and Condensation 537
- B.1.4 Dissociation 538
- B.1.5 Isotopes 539

#### B.2 Properties of Water 540

- B.2.1 Density 541
- B.2.2 Surface Tension 542
- B.2.3 Boundary-Layer Flow, Viscosity, and Turbulence 544
- B.2.4 Thermal Capacity 547
- B.2.5 Latent Heats 547
- B.2.6 Solvent Power 548
- B.3 Flow Equations 548
  - B.3.1 Ground-Water Flows 548
  - B.3.2 Open-Channel Flows 548

# Statistical Concepts Useful in Hydrology

552

C.1 Probability and Random Variables 552

#### C.2 Probability Distributions 553

- C.2.1 Discrete Random Variables 553
- C.2.2 Continuous Random Variables 553
- C.2.3 Expectation 554
- C.2.4 Quantiles 554
- C.2.5 Product Moments 557
- C.2.6 Probability-Weighted Moments and L-Moments 558
- C.3 Exceedence Probability and Return Period 560
- C.4 Covariance and Correlation 561

#### C.5 Data Analysis: Identifying an Appropriate Probability Distribution 563

- C.5.1 Sample Quantiles 563
- C.5.2 The Probability-Plot Correlation Coefficient Approach 563
- C.5.3 L-Moment Approach 565

#### C.6 Data Analysis: Estimating Parameters of Probability Distributions 566

- C.6.1 Method of Moments 566
- C.6.2 Method of Maximum Likelihood 566
- C.6.3 Method of L-Moments 566

#### C.7 The Normal Distribution 567

- C.7.1 Normal pdf and cdf 567
- C.7.2 Log-Normal Distribution 570

#### C.8 Sampling Error 570

- C.8.1 Standard Errors 571
- C.8.2 Sampling Distributions 572
- C.8.3 Confidence Intervals 573

#### C.9 Persistence and Autocorrelation 576

- C.9.1 Definition and Estimation 576
- C.9.2 Causes and Significance 576
- C.9.3 Effects of Persistence
  - on Uncertainty of Time-Series Statistics 578
- C.9.4 Effects of Persistence on Uncertainty of Correlation Estimates 579
- C.10 Statistical Criteria for Model Calibration and Validation 580
  - C.10.1 Nash-Sutcliffe Coefficient 580
  - C.10.2 Coefficient of Gain from Daily Means 580
  - C.10.3 Evaluation Measures Used in BROOK90 581

Π

## Water and Energy in the Atmosphere

#### 582

- D.1 Physics of Radiant Energy 582
- D.2 Composition and Vertical Structure of the Atmosphere 583
  - D.2.1 Composition 583
  - D.2.2 Vertical Structure 584
  - D.2.3 Pressure-Temperature Relations 584

#### D.3 Water Vapor 586

- D.3.1 Vapor Pressure 586
- D.3.2 Absolute Humidity 586
- D.3.3 Specific Humidity 586
- D.3.4 Relative Humidity 587
- D.3.5 Dew Point 587

#### D.4 Physics of Evaporation 587

- D.4.1 Mass (Water) Transfer 587
- D.4.2 Latent-Heat Transfer 589

#### D.5 Physics of Precipitation 589

- D.5.1 Cooling 590
- D.5.2 Condensation 590
- D.5.3 Droplet Growth 591
- D.5.4 Importation of Water Vapor 592

#### D.6 Physics of Turbulent Transfer Near the Ground 593

- D.6.1 Planetary Boundary Layer 593
- D.6.2 Turbulent Velocity Fluctuations 593
- D.6.3 Vertical Distribution of Wind Velocity 594
- D.6.4 Diffusion 594
- D.6.5 Momentum Transfer 596
- D.6.6 Latent-Heat Transfer 597
- D.6.7 Sensible-Heat Transfer 598
- D.6.8 Effects of Atmospheric Stability on Heat and Vapor Transfer 598
- D.6.9 Eddy Correlation 599

### E Estimation of Daily Clear-Sky Solar Radiation on Sloping Surfaces

601

- E.1 Radiation Incident on a Horizontal Plane 601
  - E.1.1 Extraterrestrial Radiation 601
  - E.1.2 Direct (Beam) Radiation at the Surface 604

- E.1.3 Diffuse Radiation 605
  - E.1.4 Global Radiation 606 E.1.5 Backscattered Radiation
  - E.1.5 Backscattered Radiation 606 E.1.6 Total Incident Radiation 606

#### E.2 Radiation on a Sloping Plane 606

- E.2.1 Equivalent Slope 606
- E.2.2 Solar Noon, Sunrise, and Sunset 606
- E.2.3 Extraterrestrial Radiation 606
- E.2.4 Total Incident Radiation at the Surface 607

#### **F** Stream-Gaging Methods for Short-Term Studies

#### 608

- F.1 Selection of Measurement Location 608
- F.2 Velocity-Area Method 609
  - F.2.1 Selection of Measurement Section 609
  - F.2.2 Method of Integration 610
  - F.2.3 Measurement of Velocity 611
  - F.2.4 Accuracy 612
- F.3. Dilution Gaging 613
- F.4 Sharp-Crested V-Notch Weirs 614
- F.5 Flumes 616
- F.6 Stage Measurement 617
  - F.6.1 Methods of Measurement 617
  - F.6.2 Measurement Location 618
  - F.6.3 Stage-Discharge Relations at Natural Controls 618

#### F.7 Slope-Area Measurements 619

- F.7.1 Standard Method 619
- F.7.2 Simplified Method 622

### G

Hydrological Websites CD-Rom

References		624
Index		640