HYDROSYSTEMS ENGINEERING AND MANAGEMENT

Larry W. Mays

Professor and Chair
Department of Civil Engineering
Arizona State University

Yeou-Koung Tung

Associate Professor, Department of Statistics
Hydrologist, Wyoming Water Research Center
University of Wyoming

BIBLIOTECA

McGraw-Hill, Inc.

New York St. Louis San Francisco Auckland Bogotá
Caracas Lisbon London Madrid Mexico Milan Montreal
New Delhi Paris San Juan Singapore Sydney Tokyo Toronto

CONTENTS

Preface xvii

Part 1 Principles

1 Introduction 3

1.1 Background 3
1.2 Descriptions of Hydrosystems 4
1.3 The Systems Concept 8
1.4 Issues in Hydrosystems Engineering 11
1.4.1 Design versus Analysis 11
1.4.2 Conventional versus Optimization Procedures 11
1.4.3 Optimization 12
1.4.4 Single-Objective versus Multiple-Objective Optimization 15
1.4.5 Uncertainties in Hydrosystem Design and Analysis 16
1.4.6 Applications of Optimization in Hydrosystems 18
1.4.7 Building a Model 18
References 20
Books on Selected Topics 20
Problems 22

2 Economics for Hydrosystems 23

2.1 Engineering Economic Analysis 23
2.2 Benefit-Cost Analysis 26
2.3 Theory of Consumer Behavior 29
2.3.1 Utility 29
2.3.2 Maximization of Utility 31
2.3.3 Demand Functions 33
2.4 Theory of the Firm 35
2.4.1 Basic Concepts 36
2.4.2 Optimal Input Combinations 40
2.4.3 Cost in the Short Run 44

2.4.4 Cost in the Long Run 46
2.4.5 Elasticities of Output and Substitution 47
2.5 Demand, Supply, and Market Equilibrium 47
References 49
Problems 50

3 Linear Programming with Applications to Hydrosystems 54

3.1 Linear Programming 54
3.1.1 Assumptions in Linear Programming Models 57
3.1.2 Forms of Linear Programming 58
3.2 Solution Algorithms for Linear Programming 60
3.2.1 Graphical Method 60
3.2.2 Feasible Extreme (or Corner) Points 62
3.2.3 Algorithm for Solving Linear Programming Problems 63
3.2.4 Basic Algorithm of Solving Linear Programming Problems 67
3.3 Simplex Method 67
3.3.1 Basic Algebraic Concepts and Setup 67
3.3.2 Algebra of Simplex Method 68
3.3.3 Summary of the Simplex Method 74
3.4 Artificial Variable Methods 75
3.4.1 Big-M Method 76
3.4.2 Two-Phase Method 77
3.5 Interpreting the Simplex Tableau 78
3.5.1 Optimal Solution 80
3.5.2 Status of Resources 80
3.5.3 Per-Unit Worth of Resources (Shadow Prices) 80
3.6 Cases of the Simplex Method Application 81
3.6.1 Degeneracy 81
3.6.2 Unbounded Solution 82
3.6.3 Alternative Optimal Solutions 83
3.6.4 Nonexisting Feasible Solutions 83
3.7 Duality of the Simplex Method 84
3.7.1 Definition of Dual Problem 84
3.7.2 Primal-Dual Relationship 85
3.8 Matrix Version of Simplex Tableau 87
3.9 New Methods for Solving Linear Programming Problems 90
References 90
Problems 91
Appendix 3A 95

4 Dynamic and Nonlinear Programming with Applications to Hydrosystems 106

4.1 Dynamic Programming 107
4.1.1 Elements of Dynamic Programming Model 108
4.1.2 Operational Characteristics of Dynamic Programming 113
4.2 Discrete Differential Dynamic Programming 120
4.3 Matrix Algebra for Nonlinear Programming 124
4.4 Unconstrained Nonlinear Optimization 130
4.4.1 Basic Concepts 130
4.4.2 One-Dimensional Search 132

	4.4.3 Multivariable Methods	135
4.5	Constrained Optimization: Optimality Conditions	138
	4.5.1 Lagrange Multiplier	138
	4.5.2 Kuhn-Tucker Conditions	140
4.6	Constrained Nonlinear Optimization: Generalized Reduced Gradient (GRG) Method	141
	4.6.1 Basic Concepts	141
	4.6.2 General Algorithms and Basis Changes	142
	4.6.3 The Reduced Gradient	144
	4.6.4 Optimality Conditions for GRG Method	146
4.7	Constrained Nonlinear Optimization: Penalty Function Methods	152
4.8	Constrained Nonlinear Optimization: Projected Lagrangian Method	155
4.9	Nonlinear Programming Codes	156
	References	157
	Problems	159
5	**Uncertainty and Reliability Analysis of Hydrosystems**	164
5.1	Review of Probability Theory	164
	5.1.1 Terminology	164
	5.1.2 Rules of Probability Computations	165
	5.1.3 Random Variables and Their Distributions	167
	5.1.4 Statistical Properties of Random Variables	169
5.2	Commonly Used Probability Distributions	175
	5.2.1 Binomial Distribution	175
	5.2.2 Poisson Distribution	176
	5.2.3 Normal Distribution	177
	5.2.4 Lognormal Distribution	178
5.3	Analysis of Uncertainties	181
5.4	Reliability Computations Using Load-Resistance Analysis	184
	5.4.1 Direct Integration Method	185
	5.4.2 Methods Using Safety Margin and Safety Factor	185
	5.4.3 First-Order Second-Moment Methods	188
	5.4.4 Dynamic (Time-Dependent) Reliability Model	190
5.5	Reliability Using Time-to-Failure Analysis	192
	5.5.1 Failure Density Function	193
	5.5.2 Failure Rate and Hazard Function	193
	5.5.3 Mean-Time-to-Failure	194
	5.5.4 Repair Density Function, Repair Rate, and Mean-Time-to-Repair	195
	5.5.5 Mean-Time-between-Failure and Mean-Time-between-Repair	196
	5.5.6 Availability and Unavailability	196
5.6	Reliability Analysis of Simple Systems	199
5.7	Optimization of Reliability	201
	5.7.1 Reliability Design with Redundancy	201
	5.7.2 Reliability Apportionment	202
5.8	Chance-Constrained Models	202
	5.8.1 Right-Hand Side Coefficients Random	203
	5.8.2 Technological Coefficients Random	205
	5.8.3 Right-Hand Side and Technological Coefficients Random	207
	References	208
	Problems	209

Part 2 Water Supply Engineering and Management

6 Water Demand Forecasting 221

6.1 Water Use and Forecasting 221
6.2 Forecasting Municipal and Industrial Water Use 224
6.2.1 Classification of Methods 224
6.2.2 General Form of Models 227
6.2.3 Data Availability 228
6.3 Regression Models for Water Use Forecasting 228
6.3.1 Regression Concepts for Water Use Forecasting 228
6.3.2 Linear Regression 233
6.3.3 Accuracy of Regression Models 237
6.3.4 General Comments about Regression Analysis 239
6.4 Cascade Models for Water Use Forecasting 241
6.4.1 Detrending 243
6.4.2 Deseasonalization 246
6.4.3 Autoregressive Filtering 250
6.4.4 Climatic Regression 253
6.4.5 Application for Monthly Water Use Forecast 256
6.5 Econometric Models for Water Demand Forecasting 257
6.5.1 Simultaneous Equations 259
6.5.2 Reduced Form Equations 260
6.5.3 Estimation of Structural Parameters 261
6.6 IWR—Main Water Use Forecasting System 262
References 266
Problems 267

7 Surface Water Systems 270

7.1 Surface Water Reservoir Systems 270
7.2 Storage-Firm Yield Analysis for Water Supply 271
7.2.1 Firm-Yield Analysis Procedures 272
7.2.2 Optimization Procedures for Firm Yield Analysis 277
7.3 Storage-Firm Energy Analysis 282
7.3.1 Concepts of Water Supply for Power Generation 282
7.3.2 Determination of Firm Energy 283
7.4 Reservoir Simulation 285
7.4.1 Operation Rules 285
7.4.2 Conservation Simulation 289
7.4.3 HEC-5 Simulation Model 290
7.5 Optimal Sizing and Operation of a Single Multiple-Purpose Reservoir 291
7.6 Optimal Sizing and Operation of Multiple-Purpose Reservoir Systems 300
7.7 Reservoir Sizing and Operation under Hydrologic Uncertainty: LP Models 302
7.7.1 Chance-Constrained Models Using Linear Decision Rules 305
7.7.2 Yield Models 312
7.8 Reservoir Operation under Hydrologic Uncertainty: DP Models 317
References 320
Problems 321

8 Groundwater Systems 323

8.1 Basic Principles of Groundwater Systems 323
8.1.1 Groundwater Hydrology 324
8.1.2 Groundwater Movement 326
8.1.3 Types of Groundwater Quantity Management Models 326
8.2 Simulation of Groundwater Systems 330
8.2.1 Development of Governing Equations 330
8.2.2 Finite Difference Equations 332
8.3 Hydraulic Management Models: Embedding Approach 334
8.3.1 Steady-State One-Dimensional Problems for Confined Aquifers 334
8.3.2 Steady-State Two-Dimensional Model for Confined Aquifers 338
8.3.3 Transient One-Dimensional Problem for Confined Aquifers 340
8.3.4 Steady-State Two Dimensional Problem for Unconfined Aquifers 342
8.4 Policy Evaluation and Allocation Models: Response Matrix Approach 343
8.5 Groundwater Management Model: Optimal Control Approach 347
References 348
Problems 350

9 Water Distribution Systems 354

9.1 Description and Purpose of Water Distribution Systems 354
9.2 Water Distribution System Components 356
9.3 Pumps and Pumping Hydraulics 359
9.4 Network Simulation 361
9.4.1 Conservation Laws 361
9.4.2 Network Equations 364
9.4.3 Network Simulation Algorithms 365
9.5 Optimization Models for Design of Branched Systems 368
9.6 Optimization Models for Design of Looped Systems 372
9.6.1 General Problems 372
9.6.2 A Linear Programming Model 373
9.7 Water Distribution System Design Model 374
9.8 Water Distribution System Reliability 378
9.8.1 Component Reliability 379
9.8.2 System Reliability 380
References 383
Problems 384

Part 3 Water Excess Engineering and Management

10 Hydrology and Hydraulics for Water Excess Management 389

10.1 Floodplain Hydrologic and Hydraulic Analysis 390
10.2 Storm Hydrograph Determination: Rainfall-Runoff Analysis 392
10.2.1 Hydrologic Losses 392
10.2.2 Unit Hydrograph Approach 395
10.2.3 U.S. Army Corps of Engineers Hydrologic Engineering Center, HEC-1 396
10.2.4 Continuous Simulation Models 399
10.3 Hydrologic Analysis: Reservoirs and Rivers 399
10.3.1 Hydrologic Reservoir Routing 399

	10.3.2 Hydrologic River Routing	400
10.4	Hydrologic Frequency Analysis for Floodplain Determination	402
	10.4.1 Flood Flow Frequency Analysis	402
	10.4.2 U.S. Water Resources Council Guidelines	403
10.5	Floodplain Elevations: Water Surface Profile Determination	408
10.6	Hydraulics of Flood Forecasting: Distributed Routing	411
10.7	U.S. National Weather Service Models for River Routing	413
	References	415
	Problems	416
11	**Urban Stormwater Management Systems**	420
11.1	Urban Stormwater Management System	420
11.2	Storm Sewer Design	421
	11.2.1 Design Philosophy	421
	11.2.2 Rational Method	423
11.3	Hydrograph Design Method	426
11.4	Minimum Cost Design of Storm Sewer Systems	428
11.5	Reliability Analysis of Storm Sewers	437
	11.5.1 Reliability Computation	437
	11.5.2 Risk-Safety Factor Relationship	442
11.6	Stormwater Detention	443
	11.6.1 Urbanization Effects and Stormwater Detention	443
	11.6.2 Selection of Detention Pond Size—Modified Rational Method	445
	11.6.3 Hydrograph Design Method	449
11.7	Minimum Cost Design of Regional Stormwater Detention Systems	450
	References	453
	Problems	454
12	**Floodplain Management Systems**	457
12.1	Flood-Control Alternatives	458
	12.1.1 Structural Alternatives	458
	12.1.2 Nonstructural Measures	461
12.2	Flood Damage Estimation	462
	12.2.1 Damage Relationships	462
	12.2.2 Expected Damages	463
12.3	HEC Flood Damage Analysis Package	466
12.4	Optimization Model for Planning Flood Control	470
12.5	Optimal Selection of Flood-Control Alternatives	473
12.6	Risk-Based Design	475
12.7	Risk-Based Design of Highway Drainage Structures	476
	12.7.1 Design of Roadway Crossing Structures	476
	12.7.2 Expected Damages and Objective Function	480
	References	483
	Problems	484

13 Operation of Surface Water Systems for Flood Control 493

13.1 Real-Time Flood Forecasting 494
13.1.1 Concepts 494
13.1.2 Real-Time Data Collection Systems for River-Lake Systems 496
13.1.3 Flood Early Warning System for Urban Areas 497
13.1.4 Flood-Forecasting Models 500
13.2 River-Reservoir Operation for Flood Control 501
13.2.1 Reservoir Operation Models 501
13.2.2 Lower Colorado River Flood Forecasting System 504
13.3 Optimization Models for Developing Operation Policies 507
13.4 Optimization Models for Real-Time Operation of Reservoirs 509
13.4.1 Optimization Model Using Hydrologic Routing 509
13.4.2 Optimization Model Using Hydraulic Routing 512
References 514
Problems 515

Author Index 519

Index 523