
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*



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

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
<hr/>		
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

The main objective of this book is to provide a comprehensive treatment of hydrosystems modeling, its engineering and management. The book is divided into two parts: Principles of Water Supply Engineering and Management and Water Excess Engineering and Management. The purpose of the first part is to provide the necessary background for the water supply and water excess parts. The purpose of the second part is to provide the necessary background for the water supply and water excess parts. The book is intended to be a textbook for students of water resources engineering and management. The book is not intended to be a review of the literature, but instead is an introduction to methods used in hydrosystems for upper level undergraduate and graduate students. The content can be presented to students with no background in operations research and hydrology and hydraulics background in hydrology and hydraulics. A major focus is to bring together the use of economics, operations research, probability and statistics with the use of hydrology, hydraulics and water resources for the analysis, design, operation, and management of various types of water projects. This book should also serve as a convenient reference for engineers, water resource planners, water resource systems analysis, and water managers.

First and foremost, this book is intended to be a textbook for students of water resources engineering and management. This book is not intended to be a review of the literature, but instead is an introduction to methods used in hydrosystems for upper level undergraduate and graduate students. The content can be presented to students with no background in operations research and hydrology and hydraulics background in hydrology and hydraulics. A major focus is to bring together the use of economics, operations research, probability and statistics with the use of hydrology, hydraulics and water resources for the analysis, design, operation, and management of various types of water projects. This book should also serve as a convenient reference for engineers, water resource planners, water resource systems analysis, and water managers.