# Table of Contents

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Preface</td>
<td>xv</td>
</tr>
<tr>
<td></td>
<td>Continuing Education Units</td>
<td>xix</td>
</tr>
<tr>
<td></td>
<td>About the Software</td>
<td>xxi</td>
</tr>
<tr>
<td>Chapter 1</td>
<td>Introduction to Water Distribution Modeling</td>
<td>1</td>
</tr>
<tr>
<td>1.1</td>
<td>Anatomy of a Water Distribution System</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Sources of Potable Water</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Customers of Potable Water</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Transport Facilities</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>What Is a Water Distribution System Simulation?</td>
<td>4</td>
</tr>
<tr>
<td>1.3</td>
<td>Applications of Water Distribution Models</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Long-Range Master Planning</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Rehabilitation</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Fire Protection Studies</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Water Quality Investigations</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Energy Management</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Daily Operations</td>
<td>7</td>
</tr>
<tr>
<td>1.4</td>
<td>The Modeling Process</td>
<td>8</td>
</tr>
<tr>
<td>1.5</td>
<td>A Brief History of Water Distribution Technology</td>
<td>10</td>
</tr>
<tr>
<td>1.6</td>
<td>What Next?</td>
<td>18</td>
</tr>
</tbody>
</table>
# Chapter 2 Modeling Theory

## 2.1 Fluid Properties

- Density and Specific Weight ........................................... 19
- Viscosity .............................................................................. 20
- Fluid Compressibility ....................................................... 22
- Vapor Pressure ..................................................................... 23

## 2.2 Fluid Statics and Dynamics

- Static Pressure ...................................................................... 23
- Velocity and Flow Regime .................................................. 26

## 2.3 Energy Concepts

- Energy Losses ...................................................................... 30

## 2.4 Friction Losses

- Darcy-Weisbach Formula ................................................... 32
- Hazen-Williams ................................................................. 34
- Manning Equation ............................................................. 37
- Comparison of Friction Loss Methods ............................... 38

## 2.5 Minor Losses

- Valve Coefficient .................................................................. 40
- Equivalent Pipe Length ...................................................... 42

## 2.6 Resistance Coefficients

- Darcy-Weisbach ................................................................. 42
- Hazen-Williams ................................................................. 43
- Manning ............................................................................. 43
- Minor Losses ...................................................................... 43

## 2.7 Energy Gains – Pumps

- Pump Head-Discharge Relationship ................................ 44
- System Head Curves ............................................................ 45
- Pump Operating Point ........................................................ 48
- Other Uses of Pump Curves ................................................. 48

## 2.8 Network Hydraulics

- Conservation of Mass ........................................................ 49
- Conservation of Energy ...................................................... 50
- Solving Network Problems .................................................. 51

## 2.9 Water Quality Modeling

- Transport in Pipes ............................................................. 52
- Mixing at Nodes ................................................................. 53
- Mixing in Tanks ................................................................. 53
- Chemical Reaction Terms .................................................. 55
- Other Types of Water Quality Simulations ...................... 61
- Solution Methods .............................................................. 63
### Chapter 3 Assembling a Model

#### 3.1 Maps and Records
- System Maps ............................................. 75
- Topographic Maps ..................................... 76
- As-Built Drawings ...................................... 76
- Electronic Maps and Records ....................... 77

#### 3.2 Model Representation
- Network Elements ..................................... 80
- Network Topology ...................................... 82

#### 3.3 Reservoirs

#### 3.4 Tanks

#### 3.5 Junctions
- Junction Elevation ..................................... 89

#### 3.6 Pipes
- Length .................................................... 91
- Diameter ............................................... 91
- Minor Losses ......................................... 94

#### 3.7 Pumps
- Pump Characteristic Curves ......................... 95
- Model Representation ................................ 98

#### 3.8 Valves
- Isolation Valves ....................................... 101
- Directional Valves .................................... 102
- Altitude Valves ....................................... 103
- Air Release Valves and Vacuum
  - Breaking Valves .................................... 104
- Control Valves ....................................... 104
- Valve Books .......................................... 107

#### 3.9 Controls (Switches)
- Pipe Controls ......................................... 107
- Pump Controls ........................................ 107
- Regulating Valve Controls .......................... 108
- Indicators of Control Settings ...................... 108

#### 3.10 Types of Simulations
- Steady-State Simulation .............................. 109
- Extended-Period Simulation ......................... 109
- Other Types of Simulations ......................... 112
# Chapter 5 Testing Water Distribution Systems

## 5.1 Testing Fundamentals

- Pressure Measurement
- Flow Measurement
- Potential Pitfalls in System Measurements

## 5.2 Fire Hydrant Flow Tests

- Pitot Gages and Diffusers
- Potential Problems with Fire Flow Tests
- Using Fire Flow Tests for Calibration

## 5.3 Head Loss Tests

- Two-Gage Test
- Parallel-Pipe Test
- Potential Problems with Head Loss Tests
- Using Head Loss Test Results for Calibration

## 5.4 Pump Performance Tests

- Head Characteristic Curve
- Pump Efficiency Testing
- Potential Problems with Pump Performance Tests
- Using Pump Performance Test Data for Calibration

## 5.5 Extended-Period Simulation Data

- Distribution System Time-Series Data
- Conducting a Tracer Test

## 5.6 Water Quality Sampling

- Laboratory Testing
- Field Studies

## 5.7 Sampling Distribution System Tanks and Reservoirs

- Water Quality Studies
- Tracer Studies
- Temperature Monitoring

## 5.8 Quality of Calibration Data
Chapter 6 Using SCADA Data for Hydraulic Modeling 235

6.1 Types of SCADA Data 236
6.2 Polling Intervals and Unsolicited Data 236
6.3 SCADA Data Format 238
6.4 Managing SCADA Data 239
6.5 SCADA Data Errors 239
   Data Compression Problems ........................................ 240
   Timing Problems ..................................................... 240
   Missing Data ......................................................... 242
   Instrumentation ...................................................... 244
   Unknown Elevations .................................................. 246
   Other Error Sources ............................................... 246
6.6 Responding to Data Problems 247
6.7 Verifying Data Validity 248

Chapter 7 Calibrating Hydraulic Network Models 251

7.1 Model-Predicted versus Field-Measured Performance 252
   Comparisons Based on Head ...................................... 252
   Location of Data Collection ..................................... 253
7.2 Sources of Error in Modeling 253
   Types of Errors ..................................................... 254
   Nominal versus Actual Pipe Diameters ......................... 255
   Internal Pipe Roughness Values ................................ 256
   Distribution of System Demands ................................. 258
   System Maps ......................................................... 260
   Temporal Boundary Condition Changes ....................... 261
   Model Skeletonization ............................................ 262
   Geometric Anomalies .............................................. 262
   Pump Characteristic Curves ..................................... 263
7.3 Calibration Approaches 263
   Manual Calibration Approaches ................................. 264
   Automated Calibration Approaches ............................. 268
   Model Validation .................................................. 278
Chapter 8  Using Models for Water Distribution System Design  297

8.1  Applying Models to Design Applications  298
  Extent of Calibration and Skeletonization  298
  Design Flow  299
  Reliability Considerations  300
  Key Roles in Design Using a Model  302
  Types of Modeling Applications  302
  Pipe Sizing Decisions  303

8.2  Identifying and Solving Common Distribution System Problems  305
  Undersized Piping  306
  Inadequate Pumping  306
  Consistent Low Pressure  307
  High Pressures During Low Demand Conditions  308
  Oversized Piping  308

8.3  Pumped Systems  310
  Pumping into a Closed System with
  No Pressure Control Valve  312
  Pumping into a Closed System with Pressure Control  313
  Variable-Speed Pumps  313
  Pumping into a System with a Storage Tank  316
  Pumping into Closed System with Pumped Storage  316
  Pumping into Hydropneumatic Tanks  318
  Well Pumping  319
  Pumps in Parallel  322
  Head Loss on Suction Side of Pump  324
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.4</td>
<td>Extending a System to New Customers</td>
<td>326</td>
</tr>
<tr>
<td></td>
<td>Extent of Analysis</td>
<td>326</td>
</tr>
<tr>
<td></td>
<td>Elevation of Customers</td>
<td>326</td>
</tr>
<tr>
<td></td>
<td>Assessing an Existing System</td>
<td>328</td>
</tr>
<tr>
<td>8.5</td>
<td>Establishing Pressure Zones and Setting Tank Overflows</td>
<td>333</td>
</tr>
<tr>
<td></td>
<td>Establishing a New Pressure Zone</td>
<td>333</td>
</tr>
<tr>
<td></td>
<td>Laying Out New Pressure Zones</td>
<td>334</td>
</tr>
<tr>
<td></td>
<td>Tank Overflow Elevation</td>
<td>337</td>
</tr>
<tr>
<td>8.6</td>
<td>Developing System Head Curves for Pump Selection/Evaluation</td>
<td>342</td>
</tr>
<tr>
<td>8.7</td>
<td>Serving Lower Pressure Zones</td>
<td>345</td>
</tr>
<tr>
<td></td>
<td>PRV Feeding into a Dead-End Pressure Zone</td>
<td>345</td>
</tr>
<tr>
<td></td>
<td>Lower Zone with a Tank</td>
<td>346</td>
</tr>
<tr>
<td></td>
<td>Lower Zone Fed with Control Valves</td>
<td>347</td>
</tr>
<tr>
<td></td>
<td>Conditions Upstream of the PRV or Control Valve</td>
<td>348</td>
</tr>
<tr>
<td>8.8</td>
<td>Rehabilitation of Existing Systems</td>
<td>348</td>
</tr>
<tr>
<td></td>
<td>Data Collection</td>
<td>349</td>
</tr>
<tr>
<td></td>
<td>Modeling Existing Conditions</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>Overview of Alternatives</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>Evaluation</td>
<td>354</td>
</tr>
<tr>
<td>8.9</td>
<td>Tradeoffs Between Energy and Capital Costs</td>
<td>354</td>
</tr>
<tr>
<td>8.10</td>
<td>Use of Models in the Design and Operation of Tanks</td>
<td>355</td>
</tr>
<tr>
<td></td>
<td>Systems Models</td>
<td>356</td>
</tr>
<tr>
<td></td>
<td>Computational Fluid Dynamics Models</td>
<td>358</td>
</tr>
<tr>
<td>8.11</td>
<td>Optimized Design and Rehabilitation Planning</td>
<td>360</td>
</tr>
<tr>
<td></td>
<td>Optimal Design Formulation</td>
<td>361</td>
</tr>
<tr>
<td></td>
<td>Optimal Design Methods</td>
<td>363</td>
</tr>
<tr>
<td></td>
<td>Optimization Issues</td>
<td>366</td>
</tr>
<tr>
<td></td>
<td>Multiple Objectives and the Treatment of the Design Optimization Problem</td>
<td>369</td>
</tr>
<tr>
<td></td>
<td>Multiobjective Decision-Making</td>
<td>370</td>
</tr>
<tr>
<td></td>
<td>Using Optimization</td>
<td>372</td>
</tr>
</tbody>
</table>
Chapter 9  Modeling Customer Systems  393

9.1  Modeling Water Meters  394
9.2  Backflow Preventers  397
9.3  Representing the Utility’s Portion of the Distribution System  398
9.4  Customer Demands  399
   Commercial Demands for Proposed Systems  399
9.5  Sprinkler Design  401
   Starting Point for Model  401
   Sprinkler Hydraulics  402
   Approximating Sprinkler Hydraulics  403
   Piping Design  404
   Fire Sprinklers  406
   Sprinkler Pipe Sizing  408
   Irrigation Sprinklers  408

Chapter 10  Operations  417

10.1  The Role of Models in Operations  417
10.2  Low Pressure Problems  419
   Identifying the Problem  419
   Modeling Low Pressures  420
   Finding Closed Valves  420
   Solving Low Pressure Problems  422
10.3  Low Fire Flow Problems  424
   Identifying the Problem  424
   Solutions to Low Fire Flow  425
10.4  Adjusting Pressure Zone Boundaries  427
10.5  Taking a Tank Off-Line  430
   Fire Flows  431
   Low Demand Problems  431
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>10.6 Shutting Down a Section of the System</strong></td>
<td>433</td>
</tr>
<tr>
<td>Representing a Shutdown</td>
<td>433</td>
</tr>
<tr>
<td>Simulating the Shutdown</td>
<td>434</td>
</tr>
<tr>
<td><strong>10.7 Power Outages</strong></td>
<td>435</td>
</tr>
<tr>
<td>Modeling Power Outages</td>
<td>435</td>
</tr>
<tr>
<td>Duration of an Outage</td>
<td>436</td>
</tr>
<tr>
<td><strong>10.8 Power Consumption</strong></td>
<td>436</td>
</tr>
<tr>
<td>Determining Pump Operating Points</td>
<td>438</td>
</tr>
<tr>
<td>Calculating Energy Costs</td>
<td>439</td>
</tr>
<tr>
<td>Multiple Distinct Operating Points</td>
<td>440</td>
</tr>
<tr>
<td>Continuously Varying Pump Flow</td>
<td>441</td>
</tr>
<tr>
<td>Developing a Curve Relating</td>
<td></td>
</tr>
<tr>
<td>Flow to Efficiency</td>
<td>442</td>
</tr>
<tr>
<td>Variable-Speed Pumps</td>
<td>443</td>
</tr>
<tr>
<td>Using Pump Energy Data</td>
<td>444</td>
</tr>
<tr>
<td>Understanding Rate Structures</td>
<td>445</td>
</tr>
<tr>
<td>Optimal Pump Scheduling</td>
<td>446</td>
</tr>
<tr>
<td><strong>10.9 Water Distribution System Flushing</strong></td>
<td>449</td>
</tr>
<tr>
<td>Modeling Flushing</td>
<td>449</td>
</tr>
<tr>
<td>Representing a Flowed Hydrant</td>
<td>449</td>
</tr>
<tr>
<td>Estimating Hydrant Discharge Using</td>
<td></td>
</tr>
<tr>
<td>Flow Emitters</td>
<td>451</td>
</tr>
<tr>
<td>Hydrant Location Relative to Nodes</td>
<td>453</td>
</tr>
<tr>
<td>Steady-State versus EPS Runs</td>
<td>454</td>
</tr>
<tr>
<td>Indicators of Successful Flushing</td>
<td>455</td>
</tr>
<tr>
<td><strong>10.10 Sizing Distribution System Meters</strong></td>
<td>457</td>
</tr>
<tr>
<td>Subsystem Metering</td>
<td>457</td>
</tr>
<tr>
<td>Using Models for Meter Sizing</td>
<td>457</td>
</tr>
<tr>
<td>Implications for Meter Selection</td>
<td>458</td>
</tr>
<tr>
<td><strong>10.11 Models for Investigation of System Contamination</strong></td>
<td>459</td>
</tr>
<tr>
<td><strong>10.12 Leakage Control</strong></td>
<td>460</td>
</tr>
<tr>
<td><strong>10.13 Maintaining an Adequate Disinfectant Residual</strong></td>
<td>462</td>
</tr>
<tr>
<td>Disinfectant Residual Assessment</td>
<td>463</td>
</tr>
<tr>
<td>Booster Chlorination</td>
<td>465</td>
</tr>
<tr>
<td>DBP Formation</td>
<td>467</td>
</tr>
<tr>
<td>Optimization Techniques</td>
<td>467</td>
</tr>
</tbody>
</table>
Chapter 11  Water System Security 499

11.1 Water System Vulnerability 499

11.2 Potential Water Security Events 500  
Physical Disruption ........................................ 500  
Contamination .................................................. 501

11.3 Assessment of Vulnerability 508  
Inspections and Checklists ................................... 510  
Formal Assessment Tools and Methods ................. 510

11.4 Application of Simulation Models 512  
Water Distribution System Models ..................... 514  
Tank and Reservoir Mixing Models ...................... 519  
Surface Water Hydraulic and Water Quality Models ........................................................................... 519

11.5 Security Measures 519

Chapter 12  Integrating GIS and Hydraulic Modeling 527

12.1 GIS Fundamentals 528  
Data Management ................................................. 530  
Geographic Data Models ..................................... 532

12.2 Developing and Maintaining an Enterprise GIS 533  
Keys to Successful Implementation ...................... 533  
Needs Assessment ............................................... 534  
Design .................................................................. 535  
Pilot Study ......................................................... 541  
Production .......................................................... 542  
Rollout ............................................................... 542

12.3 Model Construction 542  
Model Sustainability and Maintenance ................. 544  
Communication Between GIS and Modeling Staff ................................................................. 544  
Using an Existing GIS for Modeling .................... 546  
Network Components ......................................... 546  
Retrieval of Water Use Data ............................... 549  
Retrieval of Elevation Data ................................. 555  
Modeling GIS Versus Enterprise GIS .................. 557
### 12.4 GIS Analysis and Visualization 561
- Using Attributes to Create Thematic Maps 561
- Using the Spatial Coincidence of Features to Assign New Data 563
- Using Spatial Relationships Between Features to Select Certain Elements and Assign New Data 563
- Using Relationships to Trace Networks 564
- Using Combinations of GIS Capabilities to Perform Complex Analyses 565

### 12.5 The Future of GIS and Hydraulic Modeling 567

---

### Chapter 13 Transients in Hydraulic Systems 573

#### 13.1 Introduction to Transient Flow 573
- Impacts of Transients 574
- Overview of Transient Evaluation 576

#### 13.2 Physics of Transient Flow 577
- The Rigid Model 578
- The Elastic Model 579
- History of Transient Analysis Methods 583

#### 13.3 Magnitude and Speed of Transients 585
- Characteristic Time 585
- Joukowsky’s Equation 586
- Celerity and Pipe Elasticity 586
- Comparing the Elastic and Rigid Models 588
- Wave Reflection and Transmission 589
- Attenuation and Packing 597

#### 13.4 Numerical Model Calibration 600

#### 13.5 Gathering Field Measurements 602

#### 13.6 Transient Control 602
- Piping System Design and Layout 603
- Protector Devices 607

#### 13.7 Operational Considerations 615
- Flow Control Stations 616
- Air Release Valves 619
<table>
<thead>
<tr>
<th>Appendix</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appendix A</td>
<td>Units and Symbols</td>
<td>625</td>
</tr>
<tr>
<td>Appendix B</td>
<td>Conversion Factors</td>
<td>633</td>
</tr>
<tr>
<td>Appendix C</td>
<td>Tables</td>
<td>637</td>
</tr>
<tr>
<td>Appendix D</td>
<td>Model Optimization Techniques</td>
<td>643</td>
</tr>
<tr>
<td>Appendix E</td>
<td>SCADA Basics</td>
<td>685</td>
</tr>
<tr>
<td></td>
<td>Bibliography</td>
<td>703</td>
</tr>
<tr>
<td></td>
<td>Index</td>
<td>729</td>
</tr>
</tbody>
</table>