## NAZIH K. SHAMMAS • LAWRENCE K. WANG



# WATER ENGINEERING

## Hydraulics, Distribution and Treatment

**Course**Smart

WILEY

Copyright © 2016 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey, USA. Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at http://www.wiley.com/go/permission.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitners for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for the readers situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

#### Library of Congress Cataloging-in-Publication Data:

Shammas, Nazih K.
Water engineering : hydraulics, distribution, and treatment / Nazih K. Shammas, Lawrence K. Wang. pages cm
Includes bibliographical references and index.
ISBN 978-0-470-39098-6 (hardback)
I. Watervorks. 2. Drinking water. I. Wang, Lawrence K. II. Title. III. Title: Water and wastewater engineering.
TD485.W36 2015
363.6'1-dc23
2014041853

#### Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

## Contents

PREFACE XVII

#### ACKNOWLEDGMENTS XIX

1

#### 1 Introduction to Water Systems

| 1.1  | Components of Water Systems 2    |    |
|------|----------------------------------|----|
| 1.2  | Required Capacity 2              |    |
| 1.3  | Sources of Water Supply 3        |    |
| 1.4  | Rainwater 4                      |    |
| 1.5  | Surface Water 5                  |    |
|      | 1.5.1 Continuous Draft 5         |    |
|      | 1.5.2 Selective Draft 5          |    |
|      | 1.5.3 Impoundage 5               |    |
| 1.6  | Groundwater 6                    |    |
|      | 1.6.1 Springs 8                  |    |
|      | 1.6.2 Wells 8                    |    |
|      | 1.6.3 Infiltration Galleries 8   |    |
|      | 1.6.4 Recharging Devices 9       |    |
| 1.7  | Purification Works 9             |    |
| 1.8  | Transmission Works 12            |    |
| 1.9  | Distribution Works 12            |    |
|      | 1.9.1 High and Low Services      | 14 |
|      | 1.9.2 Fire Supplies 14           |    |
|      | 1.9.3 Pressures 15               |    |
|      | 1.9.4 Capacity 15                |    |
|      | 1.9.5 Service to Premises 15     |    |
| 1.10 | Water Systems Management 15      |    |
|      | 1.10.1 Municipal Supplies 15     |    |
|      | 1.10.2 Individual Small Supplies | 16 |
| 1.11 | Individual Water Systems 17      |    |
|      | Problems/Questions 18            |    |
|      | References 19                    |    |
|      |                                  |    |

#### 2 Water Sources: Surface Water 21

- 2.1 Sources of Surface Water 21
- 2.2 Safe Yield of Streams 24
- 2.3 Storage as a Function of Draft and Runoff 24
- 2.4 Design Storage 25
- 2.5 Loss by Evaporation, Seepage, and Silting 27
  - 2.5.1 Water-Surface Response 27
  - 2.5.2 Seepage 29
  - 2.5.3 Silting 29

| 2.6  | Area and Volume of Reservoirs 31       |  |  |
|------|--|--|--|
| 2.7  | Management of Catchment Areas 32       |  |  |
|      | 2.7.1 Upland Areas 32                  |  |  |
|      | 2.7.2 Lowland Areas 32                 |  |  |
|      | 2.7.3 Quality Control 32               |  |  |
|      | 2.7.4 Swamp Drainage 32                |  |  |
| 2.8  | Reservoir Siting 33                    |  |  |
| 2.9  | Reservoir Management 33                |  |  |
|      | 2.9.1 Quality Control 34               |  |  |
|      | 2.9.2 Evaporation Control 34           |  |  |
| 2.10 | Dams and Dikes 34                      |  |  |
|      | 2.10.1 Embankment Dams 34              |  |  |
|      | 2.10.2 Masonry Dams 35                 |  |  |
| 2.11 | Spillways 36                           |  |  |
| 2.12 | Intakes 37                             |  |  |
|      | 2.12.1 River Intakes 37                |  |  |
|      | 2.12.2 Lake and Reservoir Intakes 37   |  |  |
|      | 2.12.3 Submerged and Exposed           |  |  |
|      | Intakes 38                             |  |  |
|      | 2.12.4 Intake Velocities and Depths 38 |  |  |
|      | 2.12.5 Intake Conduits and Pumping     |  |  |
|      | Stations 38                            |  |  |
| 2.13 | Diversion Works 38                     |  |  |
| 2.14 | Collection of Rainwater 39             |  |  |
|      | Problems/Questions 41                  |  |  |
|      | References 42                          |  |  |
|      |  |  |  |

#### 3 Water Sources: Groundwater 45

- 3.1 Porosity and Effective Porosity 45
- 3.2 Permeability 47
- 3.3 Groundwater Geology 47
- 3.4 Groundwater Situation in The United States 48
- 3.5 Types of Aquifers 48
- 3.6 Groundwater Movement 49
- Darcy's Law 3.7 49
- 3.8 Aquifer Characteristics 50
- 3.9 Well Hydraulics 52
- 3.10 Nonsteady Radial Flow 52
  - 3.10.1 **Confined Aquifers** 52
    - 3.10.2 Semilogarithmic
      - Approximation 56
    - 3.10.3 Recovery Method 58 3.10.4
    - Unconfined Aquifers 59
      - 3.10.5 Leaky Aquifers 59

| 3.11 | Prediction            | n of Drawdown 60                 |   |
|------|-----------------------|----------------------------------|---|
|      | 3.11.1                | Constant Discharge 60            |   |
|      | 3.11.2                | Variable Discharge 61            |   |
|      | 3.11.3                | Intermittent Discharge 61        |   |
| 3.12 | Multiple-             | Well Systems 63                  |   |
| 3.13 | Aquifer Boundaries 67 |                                  |   |
| 5110 | 3 13 1                | Recharge Boundaries 67           |   |
|      | 3 13 2                | Location of Aquifer              |   |
|      | 011012                | Boundaries 69                    |   |
| 3 14 | Character             | stics of Wells 70                |   |
| 5.14 | 3 14 1                | Specific Capacity of a Well 70   |   |
|      | 3 14 2                | Partial Penetration 70           |   |
|      | 3 14 3                | Effective Well Radius 70         |   |
|      | 3.14.5                | Measurement of Well              |   |
|      | 5.14.4                | Characteristics 71               |   |
| 2.15 | Viald of              | Well 71                          |   |
| 3.15 | Yield of a            | A well /1                        |   |
|      | 3.15.1                | Maximum Available                |   |
|      |                       | Drawdown /1                      |   |
|      | 3.15.2                | Specific Capacity–Drawdown       |   |
|      |                       | Curve 72                         |   |
|      | 3.15.3                | Maximum Yield 72                 |   |
| 3.16 | Well Des              | ign 73                           |   |
| 3.17 | Well Cor              | struction 74                     |   |
|      | 3.17.1                | Dug Wells 75                     |   |
|      | 3.17.2                | Driven and Jetted Wells 75       |   |
|      | 3.17.3                | Bored Wells 75                   |   |
|      | 3.17.4                | Drilled Wells 75                 |   |
|      | 3.17.5                | Collector Wells 75               |   |
|      | 3.17.6                | Pumps 75                         |   |
|      | 3.17.7                | Development 76                   |   |
|      | 3.17.8                | Testing 76                       |   |
|      | 3.17.9                | Sanitary Protection of Wells 7   | 6 |
|      | 3.17.10               | Maintenance 76                   |   |
| 3.18 | Evaluatio             | on of Aquifer Behavior 77        |   |
|      | 3.18.1                | Hydrologic Equation 77           |   |
|      | 3.18.2                | Safe Yield of an Aquifer 77      |   |
|      | 3.18.3                | Water Budget (Hydrologic         |   |
|      |                       | Budget) 77                       |   |
| 3.19 | Groundy               | vater Quality Management 78      |   |
|      | 3,19,1                | Biological Contamination 78      |   |
|      | 3.19.2                | Subsurface Disposal of           |   |
|      | 0.117.12              | Liquid Wastes 79                 |   |
| 3 20 | Groundy               | vater Under the Direct Influence |   |
| 5.20 | of Surfa              | re Water 79                      |   |
|      | 3 20 1                | GWUDI Determination:             |   |
|      | 5.20.1                | Source Screening Phase 79        |   |
|      | 3 20 2                | GWIDI Determination:             |   |
|      | 5.20.2                | Detailed Evaluation Phase 81     |   |
|      | 3 20 3                | Hydrogeologic Assessment 81      | 1 |
|      | 3 20.4                | Water Quality Assessment 82      | - |
|      | 3 20.4                | Microscopic Particulate          |   |
|      | 5.20.5                | Analyses 82                      |   |
|      | Drohlam               | Analyses 02                      |   |
|      | Problem               | 15/Questions 04                  |   |
|      | Keleren               | ces 65                           |   |

#### 4 Quantities of Water Demand 87

| 4.1 | Design  | Period 87                         |
|-----|---------|-----------------------------------|
| 4.2 | Design  | Population 88                     |
|     | 4.2.1   | Population Data 88                |
|     | 4.2.2   | Population Growth 88              |
|     | 4.2.3   | Short-Term Population Estimates   |
|     | 4.2.4   | Long-Range Population Forecasts   |
|     | 4.2.5   | Simplified Method for Population  |
|     |         | Forecasts 92                      |
|     | 4.2.6   | Population Distribution and Area  |
|     |         | Density 92                        |
| 4.3 | Water   | Consumption 92                    |
|     | 4.3.1   | Domestic Consumption 93           |
|     | 4.3.2   | General Urban Water Demands 94    |
|     | 4.3.3   | Industrial Water Consumption 95   |
|     | 434     | Rural Water Consumption 96        |
| 4.4 | Variati | ons or Patterns of Water Demand 9 |
|     | 4.4.1   | Domestic Variations 97            |
|     | 442     | Fire Demands 98                   |
| 45  | Dema    | and Drainage Loads of             |
| 1.5 | Buildi  | ngs 104                           |
|     | Proble  | ms/Questions 106                  |

### 5 Water Hydraulics, Transmission, and Appurtenances 109

References

5.1 Fluid Mechanics, Hydraulics, and Water Transmission 109

106

- 5.1.1 Fluid Mechanics and Hydraulics
- 5.1.2 Transmission Systems 120
- 5.2 Fluid Transport 121
  - 5.2.1 Rational Equation for Surface Resistance 121
  - 5.2.2 Exponential Equation for Surface Resistance 134
  - 5.2.3 Form Resistance 145
  - 5.2.4 Hydraulic Transients 152
- 5.3 Capacity and Size of Conduits 152
- 5.4 Multiple Lines 154
- 5.5 Cross-Sections 155
- 5.6 Structural Requirements 155
- 5.7 Location 156
  - 5.7.1 Line and Grade 156
  - 5.7.2 Vertical and Horizontal Curves 1
  - 5.7.3 Depth of Cover 157
- 5.8 Materials of Construction 159
  - 5.8.1 Carrying Capacity 159
    - 5.8.2 Strength 159
    - 5.8.3 Durability 160
    - 5.8.4 Transportation 160
    - 5.8.5 Safety 160

|      | 5.8.0   | Maintenance 160                |
|------|---------|--------------------------------|
|      | 5.8.7   | Leakage 160                    |
| 5.9  | Appurt  | enances 160                    |
|      | 5.9.1   | Gate Valves 160                |
|      | 5.9.2   | Blowoffs 162                   |
|      | 5.9.3   | Air Valves 162                 |
|      | 5.9.4   | Check Valves 162               |
|      | 5.9.5   | Pressure-Reducing Valves 162   |
|      | 5.9.6   | Pressure-Sustaining Valves 163 |
|      | 5.9.7   | Pressure Breaker Valves 163    |
|      | 5.9.8   | Flow Control Valves 163        |
|      | 5.9.9   | Throttle Control Valves 163    |
|      | 5.9.10  | Manholes 163                   |
|      | 5.9.11  | Insulation Joints 163          |
|      | 5.9.12  | Expansion Joints 163           |
|      | 5.9.13  | Anchorages 163                 |
|      | 5.9.14  | Other Appurtenances 163        |
| 5.10 | Additio | nal Hydraulics Topics 164      |
|      | 5.10.1  | Measurement of Fluid Flow      |
|      |         | and Hydraulic Coefficients 164 |
|      | 5.10.2  | Forces Developed by Moving     |
|      |         | Fluids 166                     |
|      | 5.10.3  | Impulse-Momentum               |
|      |         | Principles 169                 |
|      | 5.10.4  | Drag and Lift Forces 171       |
|      | Problem | ns/Questions 172               |
|      | Referen | ces 178                        |

## Water Distribution Systems: Components, Design, and Operation 181

| 6.1 | Distril | oution Systems 181                  |
|-----|---------|-------------------------------------|
|     | 6.1.1   | One- and Two-Directional            |
|     |         | Flow 181                            |
|     | 6.1.2   | Distribution Patterns 181           |
|     | 6.1.3   | Pipe Grids 181                      |
|     | 6.1.4   | High and Low Services 181           |
|     | 6.1.5   | Service to Premises 182             |
| 6.2 | System  | n Components 183                    |
| 6.3 | System  | n Capacity 185                      |
| 6.4 | System  | n Pressure 185                      |
| 6.5 | Field I | Performance of Existing Systems 186 |
| 6.6 | Office  | Studies of Pipe Networks 187        |
|     | 6.6.1   | Sectioning 187                      |
|     | 6.6.2   | Relaxation (Hardy Cross) 190        |
|     | 6.6.3   | Pipe Equivalence 194                |
|     | 6.6.4   | Computer Programming 197            |
| 6.7 | Indust  | rial Water Systems 197              |
| 5.8 | Manag   | ement, Operation, and               |
|     | Mainte  | enance of Distribution Systems 197  |
|     | 6.8.1   | General Maintenance Person          |
|     |         | Asphyxiated While Attempting        |
|     |         | to Renair Water Leak 198            |

|     | 6.8.2    | Plumber Repairing a Water       |     |
|-----|----------|---------------------------------|-----|
|     |          | Line Killed When Struck by a    |     |
|     |          | Backhoe Bucket 199              |     |
|     | 6.8.3    | Welder Killed Following a       |     |
|     |          | 100 ft (30 m) Fall from a Water |     |
|     |          | Tower 201                       |     |
| 6.9 | Practica | al Design and Analysis of Water |     |
|     | Distrib  | ution Systems 202               |     |
|     | 6.9.1    | Minimum Design Period           |     |
|     |          | Requirements 202                |     |
|     | 6.9.2    | Water Pressure Requirements     | 202 |
|     | 6.9.3    | Minimum Size Requirements       | 202 |
|     | 6.9.4    | Velocity Requirements 203       |     |
|     | 6.9.5    | Pipes and Valves Spacing        |     |
|     |          | Requirements 203                |     |
|     | 6.9.6    | Hydrant Spacing, Location,      |     |
|     |          | and Fire Flow Requirements      | 203 |
|     | 6.9.7    | Air Relief Valve Requirements   | 203 |
|     | 6.9.8    | Depth of Cover Requirements     | 203 |
|     | 6.9.9    | Separation of Water Mains       |     |
|     |          | from Sources of                 |     |
|     |          | Contamination 203               |     |
|     | 6.9.10   | Head Loss of Water System       |     |
|     |          | Fittings 204                    |     |
|     | Problem  | ns/Questions 205                |     |
|     | Referen  | ces 210                         |     |

## 7 Water Distribution Systems: Modeling and Computer Applications 213

| 7.1 | Water  | gems Software 213              |
|-----|--------|--------------------------------|
| 7.2 | Water  | Demand Patterns 213            |
| 7.3 | Energy | Losses and Gains 214           |
| 7.4 | Pipe N | etworks 215                    |
|     | 7.4.1  | Conservation of Mass 215       |
|     | 7.4.2  | Conservation of Energy 215     |
| 7.5 | Netwo  | rk Analysis 216                |
|     | 7.5.1  | Steady-State Network           |
|     |        | Hydraulics 216                 |
|     | 7.5.2  | Extended-Period Simulation 216 |
| 7.6 | Water  | Quality Modeling 216           |
|     | 7.6.1  | Age Modeling 216               |
|     | 7.6.2  | Trace Modeling 217             |
|     | 7.6.3  | Constituents Modeling 217      |
|     | 7.6.4  | Initial Conditions 217         |
|     | 7.6.5  | Numerical Methods 217          |
|     | 7.6.6  | Discrete Volume Method 217     |
|     | 7.6.7  | Time-Driven Method 218         |
| 7.7 | Autom  | ated Optimization 218          |
|     | 7.7.1  | Model Calibration 218          |
|     | 7.7.2  | System Design 219              |

#### viii Contents

7.8 Practical Applications of Computer-Aided Water Supply System Analysis 232 Problems/Questions 233 References 240

#### Pumping, Storage, and Dual Water 8 241 Systems

| 8.1 | Pumps and Pumping Stations 241        |    |
|-----|---------------------------------------|----|
| 8.2 | Pump Characteristics 241              |    |
|     | 8.2.1 Power Requirements and          |    |
|     | Efficiencies of Pumps 244             |    |
|     | 8.2.2 Cavitation 245                  |    |
|     | 8.2.3 Performance Characteristics 24  | 46 |
| 8.3 | Service Storage 248                   |    |
|     | 8.3.1 Equalizing, or Operating,       |    |
|     | Storage 248                           |    |
|     | 8.3.2 Fire Reserve 249                |    |
|     | 8.3.3 Emergency Reserve 249           |    |
|     | 8.3.4 Total Storage 249               |    |
| 8.4 | Location of Storage 251               |    |
| 8.5 | Elevation of Storage 251              |    |
| 8.6 | Types of Distributing Reservoirs 251  |    |
| 8.7 | Dual Water Supply Systems 257         |    |
|     | 8.7.1 Background 258                  |    |
|     | 8.7.2 The Nature of the Problems with |    |
|     | Drinking Water Quality 258            |    |
|     | 8.7.3 The Pipes in the Distribution   |    |
|     | Systems 258                           |    |
|     | 8.7.4 Biofilms and the Problems They  |    |
|     | Cause 259                             |    |
|     | 8.7.5 The Proposed System 259         |    |
| 8.8 | Raw Water Intake Structures and Raw   |    |
|     | Water Pumping Wells 260               |    |
|     | Problems/Questions 262                |    |
|     | References 266                        |    |
|     |                                       |    |

#### **Cross-Connection Control** 267

- 9.1 Introduction 267
- 9.2 Public Health Significance of **Cross-Connections** 268
  - Human Blood in the Water 9.2.1 System 268
  - Sodium Hydroxide in the Water 9.2.2 Main 268
  - Heating System Antifreeze in 9.2.3 268 Potable Water
  - 9.2.4 Salt Water Pumped into Freshwater Line 269
  - 9.2.5 Paraquat in the Water System 269

|     | 9.2.6           | Propane Gas in the Water        |
|-----|-----------------|---------------------------------|
|     | 0.0.7           | Mains 270                       |
|     | 9.2.1           | Chlordane and Heptachlor at     |
|     |                 | a Housing Authority 2/1         |
|     | 9.2.8           | Boiler Water Entered High       |
|     | 21272           | School Drinking Water 2/1       |
|     | 9.2.9           | Car Wash Water in the Street    |
|     |                 | Water Main 272                  |
|     | 9.2.10          | Health Problems Due to          |
|     |                 | Cross-Connection in an          |
|     |                 | Office Building 275             |
| 9.3 | Theory          | of Backflow and                 |
|     | Backsi          | phonage 276                     |
|     | 9.3.1           | Water Pressure 276              |
|     | 9.3.2           | Siphon Theory 277               |
|     | 9.3.3           | Backflow 280                    |
| 9.4 | Method          | is and Devices for the          |
|     | Prevent         | tion of Backflow and            |
|     | Backsin         | phonage 280                     |
|     | 9.4.1           | Air Gap 281                     |
|     | 9.4.2           | Barometric Loops 281            |
|     | 9.4.3           | Atmospheric Vacuum              |
|     | 51110           | Breakers 281                    |
|     | 944             | Hose Bib Vacuum Breakers 2      |
|     | 945             | Pressure Vacuum Breakers 28     |
|     | 946             | Double Check Valves with an     |
|     | 2.4.0           | Intermediate Atmospheric        |
|     |                 | Vent 283                        |
|     | 017             | Double Check Valves 284         |
|     | 0.4.8           | Double Check Detector           |
|     | 9.4.0           | Check 284                       |
|     | 040             | Residential Dual Check 285      |
| 0.5 | 9.4.9<br>Deduce | d Pressure Principle Backflow   |
| 9.5 | Drauan          | tor 285                         |
| 0.6 | Admin           | istration of a Cross Connection |
| 9.0 | Contro          | Decare 280                      |
|     | Contro          | Program 289                     |
|     | 9.6.1           | Responsibility 289              |
|     | 9.6.2           | Dedicated Line 290              |
|     | 9.6.3           | Method of Action 290            |
| 9.7 | Pressu          | re and Leakage lests of water   |
|     | Mains           | 291                             |
|     | 9.7.1           | Preparation for Pressure and    |
|     |                 | Leakage Tests 291               |
|     | 9.7.2           | Pressure and Leakage Tests      |
|     | Proble          | ms/Questions 293                |
|     | Refere          | nces 295                        |
|     |                 |                                 |

9.3

9.4

#### Water Quality Characteristics and 10 **Drinking Water Standards** 297

- **Objectives of Water-Quality** 10.1 Management 297
- Natural Available Water Resources 29 10.2

| 10.3  | Public Health        | Issues and Drinking        |
|-------|----------------------|----------------------------|
| 1010  | Water Treatm         | ent 298                    |
| 10.4  | Physical Char        | racteristics and           |
|       | Constituents         | 300                        |
|       | 10.4.1 Co            | or 300                     |
|       | 10.4.2 Tur           | bidity and Particle        |
|       | Co                   | ant 300                    |
|       | 10.4.3 Tas           | te and Odor 301            |
|       | 10.4.4 Ter           | nperature 301              |
|       | 10.4.5 Foa           | mability 301               |
| 10.5  | Chemical Cha         | aracteristics and          |
|       | Constituents         | 301                        |
|       | 10.5.1 Me            | tals 302                   |
|       | 10.5.2 Ani           | ons 303                    |
|       | 10.5.3 Alk           | alinity and pH 304         |
|       | 10.5.4 Har           | dness, Calcium and         |
|       | Ma                   | gnesium, Carbonate and     |
|       | 1055 Tet             | arbonate 304               |
|       | 10.5.5 100           | al Dissolved Solids and    |
|       | 10.5.6 Dia           | solved Orween 205          |
|       | 10.5.7 Pes           | ticides 305                |
|       | 10.5.8 PCI           | Reference and Dioxin 305   |
|       | 10.5.9 Ash           | estos 306                  |
|       | 10.5.10 Res          | idual Disinfectants 306    |
|       | 10.5.11 Disi         | nfectant By-products 306   |
|       | 10.5.12 Oth          | er Organic and             |
|       | Inor                 | ganic Contaminants 306     |
| 10.6  | <b>Biological</b> Ch | aracteristics and          |
|       | Constituents         | 307                        |
|       | 10.6.1 Bac           | teria 307                  |
|       | 10.6.2 Prot          | ozoa (Including            |
|       | Cry                  | ptosporidium and           |
|       | Gia                  | rdia lamblia) 307          |
|       | 10.6.3 Wor           | ms 308                     |
|       | 10.6.4 Virt          | ises, Fungi, and Algae 308 |
|       | TU.U.J COI           | meter 308                  |
|       | 10.6.6 Hete          | rotrophic Plate Count      |
|       | (HP                  | C) 309                     |
|       | 10.6.7 Infe          | ctions from                |
|       | Wat                  | er-Related Sources 310     |
|       | 10.6.8 Red           | uction of Infections by    |
|       | Wate                 | er Quality                 |
|       | Man                  | agement 310                |
| 10.7  | Radiological C       | characteristics and        |
|       | Constituents         | 310                        |
| 10.8  | Drinking Wate        | r Quality Standards 311    |
| 10.9  | Industrial Wate      | er Quality Standards 313   |
| 10.10 | Bathing Water        | s 317                      |
| 10.11 | Fishing and Sh       | eiinsn Waters 317          |
| 10.12 | Quality of Wate      | as from Various            |
| 10.15 | Sources 31           | 9                          |
| 10.14 | Good Quality         | Water 320                  |
| 10.15 | Self-Purificatio     | on and Storage 320         |

| 10.16 | Objectives of Water Examination  | 321 |
|-------|----------------------------------|-----|
| 10.17 | Methods of Examination 321       |     |
| 10.18 | Standard Tests 322               |     |
| 10.19 | Expression of Analytical Results | 322 |
| 10.20 | Tapping a Source of Water 322    |     |
|       | Problems/Questions 323           |     |
|       | References 323                   |     |

#### 11 Water Treatment Systems 325

| 11.1  | Purpose o   | f Water Treatment 325         |
|-------|-------------|-------------------------------|
| 11.2  | Treatment   | of Raw Water 325              |
| 11.3  | Unit Oper   | ations and Unit Processes 328 |
| 11.4  | Gas Trans   | fer 330                       |
| 11.5  | Ion Transf  | er 330                        |
|       | 11.5.1      | Chemical Coagulation 330      |
|       | 11.5.2      | Chemical Precipitation 331    |
|       | 11.5.3      | Ion Exchange 331              |
|       | 11.5.4      | Adsorption 332                |
| 11.6  | Solute Sta  | bilization 333                |
| 11.7  | Solids Tra  | nsfer 333                     |
|       | 11.7.1      | Straining 333                 |
|       | 11.7.2      | Sedimentation 333             |
|       | 11.7.3      | Flotation 334                 |
|       | 11.7.4      | Filtration 337                |
| 11.8  | Nutrient o  | Molecular Transfer and        |
|       | Interfacial | Contact 338                   |
| 11.9  | Disinfectio | on 339                        |
| 11.10 | Miscellane  | cous Operations/Processes 340 |
| 11.11 | Coordinati  | on of Unit                    |
|       | Operation   | s/Processes 340               |
| 11.12 | Selection   | of Water Treatment            |
|       | Technolog   | ies 341                       |
|       | 11.12.1     | Treated Water                 |
|       |             | Requirements and Influent     |
|       |             | Characteristics 341           |
|       | 11.12.2     | Existing System               |
|       |             | Configuration 341             |
|       | 11.12.3     | Water Treatment Costs 341     |
|       | 11.12.4     | Operation Requirements 341    |
|       | 11.12.5     | Pretreatment and              |
|       |             | Posttreatment Processes 341   |
|       | 11.12.6     | Waste Management 342          |
|       | 11.12.7     | Future Service Area Needs 342 |
| 11.13 | Control of  | Turbidity, Color, and         |
|       | Biological  | Contamination 342             |
| 11.14 | Organic Co  | ontaminant Removal 343        |
| 11.15 | Inorganic ( | Contaminant Removal and       |
|       | Control     | 345                           |
|       | 11.15.1     | Corrosion Controls 345        |
|       | 11.15.2     | norganic Contaminant          |
|       | 1           | Removal 345                   |
|       | 11.15.3     | Radionuclides Removal         |
|       | 2           | and Risk Control 345          |

| x | Contents |  |
|---|----------|--|
|   | Contents |  |

| 11.16 | Water Renovation 348        |     |
|-------|-----------------------------|-----|
| 11.17 | Treatment Kinetics 350      |     |
| 11.18 | Monitoring Water Quality    | 351 |
| 11.19 | Distribution to Customers   | 352 |
| 11.20 | Glossary of Water Treatment | nt  |
|       | Systems 352                 |     |
|       | Problems/Questions 35       | 9   |
|       | References 360              |     |
|       |                             |     |

## 12 Chemicals Feeding, Mixing, and Flocculation 363

| 1  | 2.1    | Introduc | ction 363                    |     |
|----|--------|----------|------------------------------|-----|
| 1  | 2.2    | Chamio   | g, Storing, and recuing      |     |
|    |        | 12.2.1   | Points of Chemical           |     |
|    |        | 12.2.1   | Addition 364                 |     |
|    |        | 1222     | Chamical Matering            |     |
|    |        | 12.2.2   | Equipment 364                |     |
|    |        | Denida   | Equipment 504                |     |
| 1  | 2.3    | Rapid N  | Machanical Minara 260        |     |
|    |        | 12.3.1   | Mechanical Mixers 309        |     |
|    |        | 12.3.2   | In-Line Static Mixers 370    |     |
|    |        | 12.3.3   | In-Line Mechanical           |     |
|    |        |          | Blenders 3/1                 |     |
|    |        | 12.3.4   | Jet Injection Blending 3/1   |     |
|    |        | 12.3.5   | Coagulant Diffusers 372      |     |
|    |        | 12.3.6   | Hydraulic Jumps 372          | 270 |
| 1  | 2.4    | Rapid N  | fixing and Slow Flocculation | 312 |
| 1  | 2.5    | Floccul  | ation 373                    |     |
| 1  | 2.6    | Mixing   | and Stirring Devices 373     |     |
|    |        | 12.6.1   | Baffled Channels 373         |     |
|    |        | 12.6.2   | Pneumatic Mixing and         |     |
|    |        |          | Stirring 374                 |     |
|    |        | 12.6.3   | Mechanical Mixing and        |     |
|    |        |          | Stirring 374                 |     |
| 1  | 2.7    | Floccul  | ator Performance 391         |     |
|    |        | 12.7.1   | Mixing 391                   |     |
|    |        | 12.7.2   | Flocculator Inlet and Outlet |     |
|    |        |          | Structures 392               |     |
|    |        | 12.7.3   | Improving Basin Circulation  |     |
|    |        |          | with Baffles 392             |     |
| 1  | 2.8    | Costs    | 393                          |     |
|    |        | Probler  | ns/Questions 394             |     |
|    |        | Referen  | nces 395                     |     |
|    |        |          |                              |     |
|    |        |          |                              |     |
| 13 | Aerati | on, Gas  | Transfer, and                |     |
| ,  | Oxida  | tion     | 397                          |     |

| 13.1 | Sources of Gases in Water 397      |     |
|------|------------------------------------|-----|
| 13.2 | Objectives of Gas Transfer 397     |     |
| 13.3 | Absorption and Desorption of Gases | 398 |

| 13.4  | Rates of Gas Absorption and         |
|-------|-------------------------------------|
|       | Desorption 400                      |
| 13.5  | Types of Aerators 402               |
|       | 13.5.1 Gravity Aerators 402         |
|       | 13.5.2 Spray Aerators 402           |
|       | 13.5.3 Air Diffusers 402            |
|       | 13.5.4 Mechanical Aerators 404      |
| 13.6  | Factors Governing Gas Transfer 405  |
| 13.7  | Design of Gravity Aerators 405      |
| 13.8  | Design of Fixed-Spray Aerators 406  |
| 13.9  | Design of Movable-Spray Aerators 40 |
| 13.10 | Design of Injection Aerators 407    |
| 13.11 | Mechanical Aerators 408             |
| 13.12 | Oxidation for Removal of Dissolved  |
|       | Iron and Manganese 408              |
|       | 13.12.1 Solubility of Fe and Mn 408 |
|       | 13.12.2 Redox Reactions of Fe and   |
|       | Mn 409                              |
|       | 13.12.3 Precipitation of Fe and Mn  |
|       | 13.12.4 Kinetics of Oxygenation 40  |
|       | 13.12.5 Engineering Management      |
|       | of Oxidative Removal of             |
|       | Iron and Manganese 409              |
| 13.13 | Removal of Specific Gases 411       |
|       | 13.13.1 Methane 411                 |
|       | 13.13.2 Carbon Dioxide 411          |
|       | 13.13.3 Hydrogen Sulfide 411        |
| 13.14 | Removal of Odors and Tastes 414     |
|       | Problems/Questions 414              |

| 1 | Problems/Qu | estions | 414 |
|---|-------------|---------|-----|
| 1 | References  | 415     |     |

## 14 Coagulation 417

| 14.1 | Introduction 417                     |     |
|------|--------------------------------------|-----|
| 14.2 | The Colloidal State 417              |     |
|      | 14.2.1 Electrokinetic Properties     | of  |
|      | Colloids 417                         |     |
|      | 14.2.2 Hydration 418                 |     |
|      | 14.2.3 Tyndall Effect 418            |     |
|      | 14.2.4 Brownian Movement             | 418 |
|      | 14.2.5 Filterability 418             |     |
| 14.3 | Colloidal Structure and Stability of |     |
|      | Colloids 418                         |     |
| 14.4 | Destabilization of Colloids 421      |     |
|      | 14.4.1 Double-Layer                  |     |
|      | Compression 421                      |     |
|      | 14.4.2 Adsorption and Charge         |     |
|      | Neutralization 422                   |     |
|      | 14.4.3 Entrapment of Particles i     | n   |
|      | Precipitate 422                      |     |
|      | 14.4.4 Adsorption and Bridging       |     |
|      | between Particles 42                 | 2   |

| 14.5 | Influen | cing Factors 423                   |
|------|---------|------------------------------------|
|      | 14.5.1  | Colloid Concentration 423          |
|      | 14.5.2  | Alkalinity and pH 423              |
|      | 14.5.3  | Coagulant Dosage and pH 423        |
|      | 14.5.4  | Zeta Potential 424                 |
|      | 14.5.5  | Affinity of Colloids for Water 424 |
|      | 14.5.6  | Anions in Solution 425             |
|      | 14.5.7  | Cations in Solution 425            |
|      | 14.5.8  | Temperature 425                    |
| 14.6 | Coagul  | ants 425                           |
|      | 14.6.1  | Aluminum Salts 426                 |
|      | 14.6.2  | Iron Salts 427                     |
|      | 14.6.3  | Sodium Aluminate 430               |
|      | 14.6.4  | Magnesium Coagulant 430            |
|      | 14.6.5  | Polymeric Inorganic Salts 430      |
|      | 14.6.6  | Organic Polymers 431               |
|      | 14.6.7  | Coagulant Aids 432                 |
| 14.7 | Coagula | ation Control 432                  |
|      | 14.7.1  | Jar Test 433                       |
|      | 14.7.2  | Zetameter 433                      |
|      | 14.7.3  | Streaming Current Detector 434     |
|      | 14.7.4  | Colloid Titration for              |
|      |         | Polyelectrolyte Determination      |
|      |         | and Coagulation Control 434        |
|      | Problem | ns/Questions 435                   |
|      | Special | Reference 436                      |
|      | Referen | ces 436                            |

## 15 Screening, Sedimentation, and Flotation 439

| 15.1 | Treatm   | ent Objectives 439              |
|------|----------|---------------------------------|
| 15.2 | Screen   | ing 439                         |
| 15.3 | Sedime   | entation 439                    |
| 15.4 | Types of | of Sedimentation 439            |
|      | 15.4.1   | Settling Velocities of Discrete |
|      |          | Particles-Class 1               |
|      |          | Clarification 440               |
|      | 15.4.2   | Hindered Settling of Discrete   |
|      |          | Particles—Class 2               |
|      |          | Clarification 443               |
|      | 15.4.3   | Settling of Flocculent          |
|      |          | Suspensions—Zone Settling 445   |
|      | 15.4.4   | Compression Settling 446        |
| 15.5 | Settling | Basins 447                      |
|      | 15.5.1   | Efficiency of Ideal Settling    |
|      |          | Basins 447                      |
|      | 15.5.2   | Reduction in Settling           |
|      |          | Efficiency by Currents 448      |
|      | 15.5.3   | Short-Circuiting and Basin      |
|      |          | Stability 449                   |
|      | 15.5.4   | Scour of Bottom Deposits 450    |
|      | 15.5.5   | Elements of Tank Design 451     |

| 15.6  | Upflow Clarification 451             |   |
|-------|--------------------------------------|---|
| 15.7  | General Dimensions of Settling       |   |
|       | Tanks 455                            |   |
| 15.8  | Sludge Removal 456                   |   |
| 15.9  | Inlet Hydraulics 456                 |   |
| 15.10 | Outlet Hydraulics 459                |   |
| 15.11 | Sedimentation Tank Loading,          |   |
|       | Detention, And Performance 459       |   |
|       | 15.11.1 Sedimentation Tank           |   |
|       | Performance 459                      |   |
|       | 15.11.2 Regulations and Standards 46 | 0 |
| 15.12 | Shallow Depth Settlers 462           |   |
|       | 15.12.1 Theory of Shallow Depth      |   |
|       | Settling 462                         |   |
|       | 15.12.2 Tube Settlers 463            |   |
|       | 15.12.3 Lamella Separator 464        |   |
| 15.13 | Gravity Thickening of Sludge 464     |   |
| 15.14 | Natural Flotation 467                |   |
| 15.15 | Dissolved Air Flotation Process 468  |   |
|       | 15.15.1 Process Description 468      |   |
|       | 15.15.2 Process Configurations 468   |   |
|       | 15.15.3 Factors Affecting            |   |
|       | Dissolved Air Flotation 469          |   |
|       | 15.15.4 Dissolved Air Flotation      |   |
|       | Theory 469                           |   |
|       | 15.15.5 Flotation Design,            |   |
|       | Operation, and                       |   |
|       | Performance 474                      |   |
|       | 15.15.6 Municipal Potable Water      |   |
|       | Plants 475                           |   |
|       | Problems/Questions 480               |   |
|       | References 482                       |   |

## 16 Conventional Filtration 485

| 16.1 | Granular Water Filters 485  |
|------|---|
| 16.2 | Granular Wastewater Filters 487   |
| 16.3 | Granular Filtering Materials 488  |
|      | 16.3.1 Grain Size and Size  |
|      | Distribution 488  |
|      | 16.3.2 Grain Shape and Shape  |
|      | Variation 489   |
| 16.4 | Preparation of Filter Sand 490  |
| 16.5 | Hydraulics of Filtration 491  |
|      | 16.5.1 Hydraulics of Stratified   |
|      | Beds 492  |
|      | 16.5.2 Hydraulics of Unstratified   |
|      | Beds 493  |
| 16.6 | Hydraulics of Fluidized Beds-Filter   |
|      | Backwashing 494   |
| 16.7 | Removal of Impurities 497   |
| 16.8 | Kinetics of Filtration 497  |
|      | A CONTRACT OF A |

| 16.9  | Filter Design 498             |                             |        |  |  |
|-------|-------------------------------|-----------------------------|--------|--|--|
|       | 16.9.1                        | Bed Depth 498               |        |  |  |
|       | 16.9.2                        | Underdrainage System        | is 500 |  |  |
|       | 16.9.3                        | Scour Intensification       | 503    |  |  |
|       | 16.9.4                        | Washwater Troughs           | 503    |  |  |
|       | 16.9.5                        | Filter and Conduit          |        |  |  |
|       |                               | Dimensions 505              |        |  |  |
| 16.10 | Filter Appurtenances and Rate |                             |        |  |  |
|       | Control                       | 505                         |        |  |  |
| 16.11 | Length o                      | of Filter Run 506           |        |  |  |
| 16.12 | Filter Troubles 507           |                             |        |  |  |
| 16.13 | Plant Performance 508         |                             |        |  |  |
|       | 16.13.1                       | <b>Bacterial Efficiency</b> | 508    |  |  |
|       | 16.13.2                       | Removal of Color,           |        |  |  |
|       |                               | Turbidity, and Iron         | 509    |  |  |
|       | 16.13.3                       | Removal of Large            |        |  |  |
|       |                               | Organisms 509               |        |  |  |
|       | 16.13.4                       | Oxidation of Organic        |        |  |  |
|       |                               | Matter 509                  |        |  |  |
|       | Problem                       | s/Questions 509             |        |  |  |
|       | References 510                |                             |        |  |  |

### 17 Alternative and Membrane Filtration Technologies 513

| 17.1 | Introduction of Filtration |                                |     |  |  |
|------|----------------------------|--------------------------------|-----|--|--|
|      | Technolo                   | ogies 513                      |     |  |  |
|      | 17.1.1                     | Filtration Overview            | 513 |  |  |
|      | 17.1.2                     | <b>Filtration Applications</b> | 513 |  |  |
| 17.2 | Direct F                   | iltration 514                  |     |  |  |
|      | 17.2.1                     | Process Description            | 514 |  |  |
|      | 17.2.2                     | System Performance             | 516 |  |  |
| 17.3 | Slow Sand Filtration 516   |                                |     |  |  |
|      | 17.3.1                     | Process Description            | 516 |  |  |
|      | 17.3.2                     | System Performance             | 516 |  |  |
|      | 17.3.3                     | System Design                  |     |  |  |
|      |                            | Considerations 517             | 7   |  |  |
|      | 17.3.4                     | Operation and                  |     |  |  |
|      |                            | Maintenance 518                |     |  |  |
| 17.4 | Package                    | Plant Filtration 518           |     |  |  |
|      | 17.4.1                     | General Process                |     |  |  |
|      |                            | Description 518                |     |  |  |
|      | 17.4.2                     | Conventional Filtration        | n   |  |  |
|      |                            | Package Plants 519             | 9   |  |  |
|      | 17.4.3                     | Tube-Type Clarifier            |     |  |  |
|      |                            | Package Plants 519             | 9   |  |  |
|      | 17.4.4                     | Adsorption Clarifier-Filter    |     |  |  |
|      |                            | Package Plant 519              |     |  |  |
|      | 17.4.5                     | Dissolved Air                  |     |  |  |
|      |                            | Flotation-Filtration           |     |  |  |
|      |                            | Package Plant 520              |     |  |  |
|      | 17.4.6                     | Operation and Maintenance      |     |  |  |
|      |                            | of Package Plants              | 522 |  |  |
|      |                            | -                              |     |  |  |

|      | 17.4.7                               | General System Performance        |  |  |  |
|------|--------------------------------------|-----------------------------------|--|--|--|
|      |                                      | of Package Plants 522             |  |  |  |
| 17.5 | Diatom                               | Diatomaceous Earth Filtration 524 |  |  |  |
|      | 17.5.1                               | Process Description 524           |  |  |  |
|      | 17.5.2                               | Operation and Maintenance 52      |  |  |  |
| 17.6 | Cartridge Filtration 526             |                                   |  |  |  |
|      | 17.6.1                               | Cartridge Filtration              |  |  |  |
|      |                                      | Applications 526                  |  |  |  |
|      | 17.6.2                               | Operation and Maintenance         |  |  |  |
|      |                                      | of Cartridge Filtration 526       |  |  |  |
| 17.7 | Membrane Filtration 527              |                                   |  |  |  |
|      | 17.7.1                               | Process Description 527           |  |  |  |
|      | 17.7.2                               | System Design                     |  |  |  |
|      |                                      | Considerations 527                |  |  |  |
|      | 17.7.3                               | Operation of Membrane             |  |  |  |
|      |                                      | Filtration 531                    |  |  |  |
|      | 17.7.4                               | Maintenance of Membrane           |  |  |  |
|      |                                      | Filtration Systems 537            |  |  |  |
|      | 17.7.5                               | Membrane Filtration               |  |  |  |
|      |                                      | Applications 538                  |  |  |  |
|      | 17.7.6                               | System Performance of             |  |  |  |
|      |                                      | Membrane Filtration 539           |  |  |  |
|      | 17.7.7                               | Potential Problems of             |  |  |  |
|      |                                      | Membrane Filtration 540           |  |  |  |
| 17.8 | Selecting the Appropriate Filtration |                                   |  |  |  |
|      | Treatment System 540                 |                                   |  |  |  |
|      | 17.8.1                               | Steps in an Evaluation 540        |  |  |  |
|      | 17.8.2                               | Need for Pilot Studies 540        |  |  |  |
|      | 17.8.3                               | Flocculation, Sedimentation,      |  |  |  |
|      |                                      | and Flotation Studies 541         |  |  |  |
|      | 17.8.4                               | Filtration Studies 541            |  |  |  |
|      | Proble                               | ms/Questions 541                  |  |  |  |
|      | Refere                               | nces 542                          |  |  |  |
|      |                                      |                                   |  |  |  |

### 18 Disinfection and Disinfection By-products Control 545

- 545 18.1 Purpose of Disinfection Pathogens, Disinfection, and 18.2 Disinfectants 545 18.3 Disinfection by Heat 546 18.4 Disinfection by Ultraviolet Light 546 Disinfection by Chemicals 546 18.5 **Oxidizing Chemicals** 546 18.5.1 18.5.2 Metal Ions 547 18.5.3 Alkalis and Acids 547 18.5.4 Surface-Active Chemicals 54 Advanced Oxidation 18.5.5 547 Processes 548 Theory of Chemical Disinfection 18.6 549 Kinetics of Chemical Disinfection 18.7 Time of Contact 549 18.7.1 18.7.2
  - 8.7.2 Concentration of Disinfectant 551