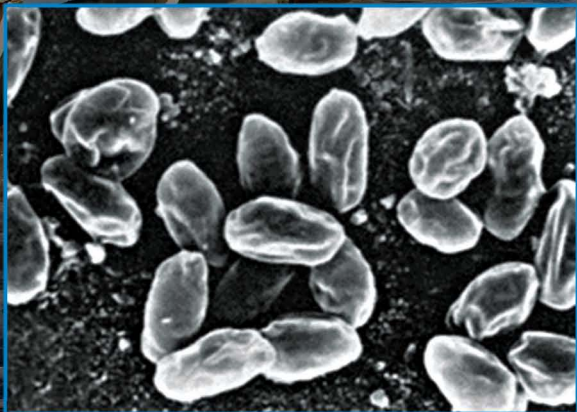
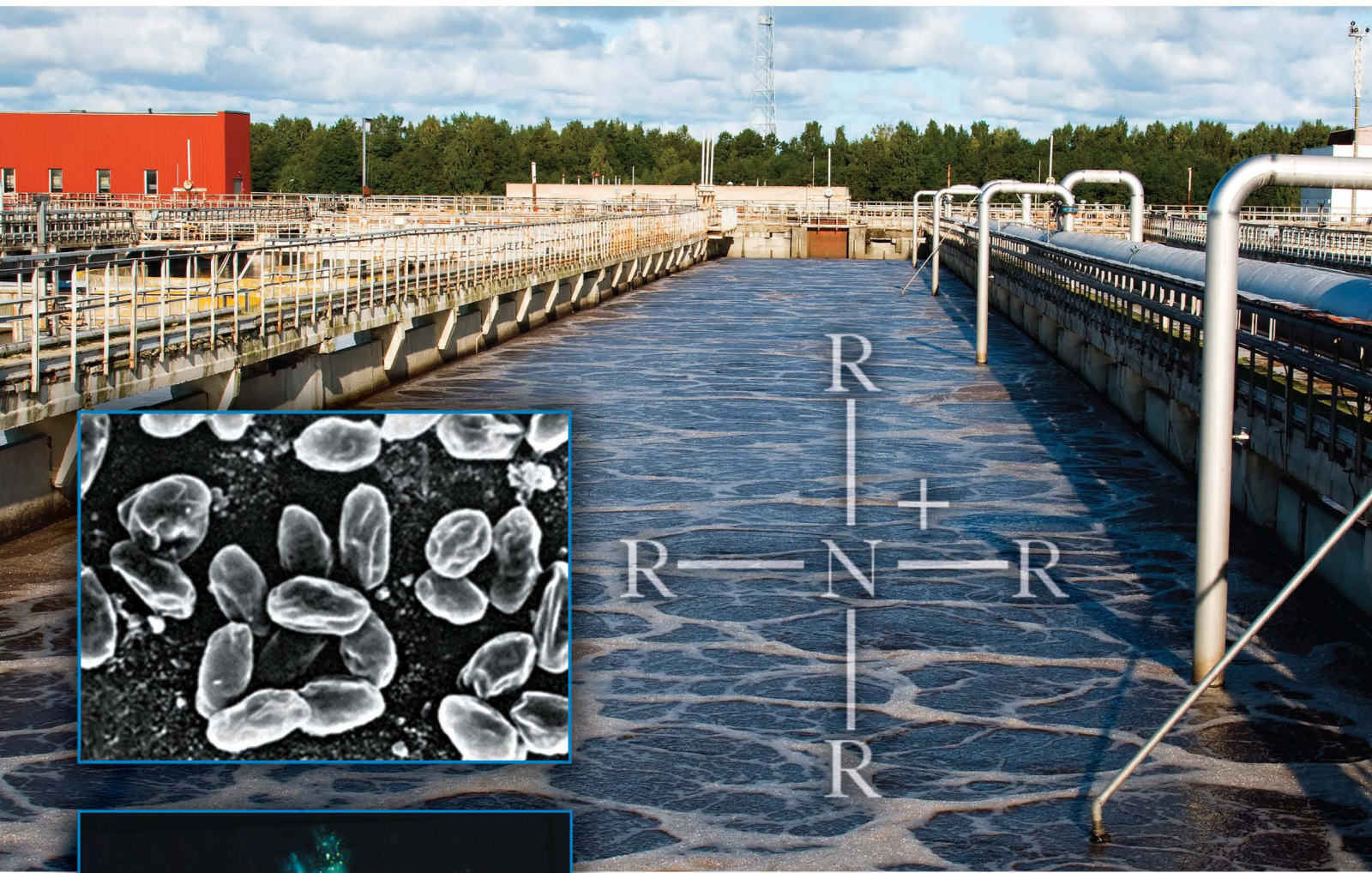


Fundamentals of Water Treatment Unit Processes

Physical, Chemical, and Biological



David Hendricks

 CRC Press
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Contents

Preface	xxxiii
Acknowledgments	xxxv
Author	xxxvii
Downloadable Files	xxxix
Contents—Downloadable Files	xli

PART I *Foundation*

Chapter 1	Water Treatment	3
1.1	Water Treatment In-a-Nutshell	3
1.1.1	Water Treatment Plants	3
1.1.2	Residuals	3
1.2	Organization of Water Treatment Knowledge	3
1.3	Unit Processes	4
1.3.1	Definitions	4
1.3.2	Technologies	5
1.3.3	Breadth of Unit Processes and Technologies	5
1.3.4	Proprietary Technologies	5
1.3.5	Status of Unit Processes	7
1.3.6	Future of Treatment	8
1.3.7	Energy Expenditure for Treatment	8
1.4	Treatment Trains	8
1.4.1	Tertiary Treatment	9
1.4.1.1	Cases	9
1.4.2	Industrial Wastewater Treatment	10
1.4.2.1	Cases	11
1.4.3	Industrial Process Water Treatment	12
1.4.4	Hazardous Wastes	12
1.4.5	Hazardous Wastes: In Situ Treatment	13
1.5	Design	13
1.5.1	Factors: Nontechnical	13
1.5.1.1	Operation Issues	13
1.5.1.2	Managing a Team	13
1.5.1.3	Expansion	13
1.5.1.4	Esthetics	13
1.5.1.5	Regulations	14
1.5.1.6	Institutions	14
1.5.1.7	Consulting Engineering	14
1.6	Summary	17
	Problems	17
	Acknowledgments	18
	Glossary	18
	References	19
Chapter 2	Water Contaminants	21
2.1	Water Quality: Definitions	21
2.1.1	Contaminants	21
2.1.2	State of Water	22

2.1.3	Criteria	22
2.1.4	Standards	22
2.1.4.1	Kinds of Water Quality Standards.....	22
2.1.4.2	Normative Standards.....	24
2.1.4.3	Standards as Targets for Treatment	24
2.1.5	Surrogates	24
2.2	Federal Laws.....	25
2.2.1	Legal Definitions	26
2.2.2	Regulations	26
2.2.3	Priority Pollutants	26
2.3	Maturation of Water Quality Knowledge.....	27
2.3.1	Knowledge of Contaminants	27
2.3.2	Measurement Technologies	28
2.4	Categorizations of Contaminant Species.....	28
2.4.1	Systems of Categorization.....	28
2.4.2	Illustrative System of Contaminant Categorization	28
2.5	Utility of Water Quality Data.....	31
2.5.1	Contaminants and Water Uses	31
2.6	Combinations of Quality of Source Waters and Product Waters	31
	Problems	34
	Acknowledgments	34
	Appendix 2.A: Organic Carbon as a Contaminant	34
2.A.1	Categories of Organics in Water	35
2.A.1.1	Color	37
2.A.1.2	Organic Carbon.....	37
2.A.1.3	UV ₂₅₄	37
2.A.1.4	Synthetic Organic Carbon.....	37
2.A.2	Disinfection By-Products	37
2.A.3	Disinfection By-Products in Secondary Effluents.....	39
2.A.4	Disinfectant Selection.....	40
2.A.5	Other Notes.....	40
	Glossary	40
	References	41
	Bibliography	42
Chapter 3	Models	45
3.1	Unit Processes.....	45
3.2	Models	45
3.2.1	Categories of Models	45
3.2.2	The Black Box.....	45
3.2.2.1	Plots.....	46
3.2.3	Physical Models	46
3.2.3.1	Bench Scale Testing	46
3.2.3.2	Pilot Plants	46
3.2.3.3	Demonstration Plants	47
3.2.4	Mathematical Models	48
3.2.5	Computer Models	48
3.2.6	Scenarios.....	49
3.3	Modeling Protocol	49
3.3.1	Spreadsheets	51
3.4	Units and Dimensions	52
3.4.1	Units	52
3.4.2	Dimensions	52

3.5	Examples of Models	52
3.6	Summary	54
	Problems	54
	Glossary	54
	References	56
Chapter 4	Unit Process Principles.....	57
4.1	Unit Processes.....	57
4.1.1	Spectrum of Unit Processes and Technologies	57
4.1.2	Matching Unit Process with Contaminant	57
4.1.2.1	Contextual Changes and New Treatment Demands.....	57
4.2	Principles	57
4.2.1	Sinks	57
4.2.2	Transport.....	59
4.2.2.1	Macro Transport: Sedimentation	59
4.2.2.2	Macro Transport: Advection.....	59
4.2.2.3	Macro Transport: Turbulent Diffusion	59
4.2.2.4	Macro Transport: Porous Media Dispersion.....	59
4.2.2.5	Molecular Transport: Diffusion	59
4.2.2.6	Mathematics of Diffusion, Turbulence, and Dispersion.....	60
4.2.3	Summary.....	62
4.3	Reactors	62
4.3.1	Examples of Reactors.....	62
4.3.2	Types of Reactors.....	62
4.3.3	Mathematics of Reactors	62
4.3.3.1	Materials Balance: Concept.....	62
4.3.3.2	Comments on Materials Balance	63
4.3.3.3	Materials Balance: Mathematics	63
4.3.4	Materials Balance: Special Conditions.....	66
4.3.4.1	Batch Reactor: Complete Mixed	66
4.3.4.2	Steady State Reactor: Complete Mixed.....	66
4.3.4.3	Zero Reaction: Complete Mixed	67
4.3.4.4	Nonsteady State Reactor	67
4.3.4.5	Spreadsheet Method to Solve Finite Difference Form of Mass Balance Equation	68
4.3.4.6	Utility of Finite Difference Equation and Tracer Tests.....	71
4.4	Kinetic Models	71
4.4.1	First-Order Kinetics	71
4.4.2	Second-Order Kinetics	72
4.4.3	Examples of Kinetic Equations	72
4.4.3.1	Example: Gas Transfer	72
4.4.3.2	Example: Biological Degradation of Substrate	72
4.4.3.3	Example: Trickling Filter.....	72
	Problems	73
	Glossary	74
	References	76

PART II *Particulate Separations*

Chapter 5	Screening	79
5.1	Theory of Screening	79
5.2	Types of Screens	79
5.2.1	Bar Screens.....	79
5.2.1.1	Cleaning	80
5.2.1.2	Manually Cleaned Bar Screens.....	80

5.2.1.3	Screenings	80
5.2.1.4	Bar Size	80
5.2.1.5	Hydraulic Design	81
5.3	Comminutors	82
5.3.1	Design	82
5.4	Fine Screens	83
5.4.1	Drum Screens and Disk Screens	83
5.4.2	Wedge-Wire Static Screens	83
5.4.2.1	Mathematical Relationships	85
5.4.2.2	Theory	85
5.4.2.3	Design	85
5.5	Microscreens	86
5.5.1	Equipment and Installation	86
5.5.2	Applications	86
5.5.3	Performance	86
5.5.4	Operation	86
5.5.5	Sizing	87
5.5.6	Operating Data	87
5.5.7	Microscreen Model	88
5.5.7.1	Interpretation of Model Results	91
Problems	.....	92
Bar Screens	.....	92
Acknowledgments	.....	93
Glossary	.....	93
References	.....	93

Chapter 6	Sedimentation	95
6.1	Key Notions in Design	95
6.2	Particle Settling	95
6.2.1	Particle Settling Principles	95
6.2.2	Stokes' Law	95
6.2.3	Suspensions	97
6.2.3.1	Type I: Discrete Particle Suspensions	97
6.2.3.2	Type II: Flocculent Suspensions	98
6.2.3.3	Type III: Hindered Settling	98
6.2.3.4	Type IV: Compression Settling	99
6.3	Settling Basins	99
6.3.1	The Ideal Basin	99
6.3.1.1	Camp's Conditions for the Ideal Basin	99
6.3.1.2	Overflow Velocity	99
6.3.1.3	Significance of Overflow Velocity	101
6.3.1.4	Insignificance of Detention Time	101
6.3.1.5	Partial Removals for Particles with Fall Velocities, $v_s < v_o$	101
6.4	Characterizing Suspensions	103
6.4.1	Characteristics of Discrete Particle Suspensions and Removal Analysis	103
6.4.2	Graphic Depiction of Size Fraction Removed	103
6.4.3	Mathematics of Removal	104
6.4.4	Up-Flow Basins: A Special Case	105
6.4.5	The Role of Ideal Settling Basin Theory	105
6.5	Flocculent Suspensions (Type II)	106
6.5.1	Settling Test for a Flocculent Suspension	106
6.5.2	Determining Percent Removals	106
6.6	Hindered and Compression Settling (Type III and Type IV Suspensions)	107
6.6.1	Settling Velocity as Affected by Solids Concentration	108
6.6.1.1	Settling Tests	108
6.6.1.2	Characterizing Settling Velocity	108

6.6.2	Final Settling as Affected by Limiting Flux Density	108
6.6.2.1	Activated Sludge	109
6.6.2.2	Final Settling Basin Processes	109
6.6.2.3	Mass Balance Relations	109
6.6.2.4	Limiting Flux Density	110
6.6.2.5	Limiting Flux Density: Evaluation Procedure	110
6.6.2.6	Example of Limiting Flux Density Using Plots	111
6.7	Hydraulics of Settling Basins	112
6.7.1	Flow Patterns and Short Circuiting	113
6.7.2	Density Currents	113
6.7.3	Dispersion Tests Using a Tracer	113
6.7.3.1	Results of Dispersion Tests	113
6.7.4	Computational Fluid Dynamics	114
6.8	Design Practice	114
6.8.1	Categories of Basins	114
6.8.2	Examples of Designs	115
6.8.2.1	Horizontal Flow	115
6.8.2.2	Up-Flow	115
6.8.2.3	Data from Real Basins	115
6.8.3	Guidelines and Criteria for Design	115
6.8.3.1	Discrete Particle Suspensions: Type I	118
6.8.3.2	Flocculent Suspensions: Type II	118
6.8.3.3	Flocculent Suspensions—Hindered Settling: Type III	118
6.8.3.4	Compression Settling: Type IV	118
6.9	Real Basins	118
6.9.1	Inlet Design	119
6.9.2	Outlet Design	121
6.9.3	Summary Notes for Practical Design	122
6.10	Plate Settlers and Tube Settlers	122
6.10.1	Plate Settlers	122
6.10.1.1	Particle Path: Analysis	122
6.10.1.2	Sludge Removal	123
6.10.1.3	Plate Settler Systems	123
6.10.1.4	Sizes of Units	124
6.10.1.5	Surface Overflow Rates	124
6.10.1.6	Theory	124
6.10.2	Tube Settlers	127
	Problems	128
	Acknowledgments	130
	Glossary	130
	References	132

Chapter 7 Grit Chambers 135

7.1	Grit	135
7.2	Horizontal Flow Grit Chambers	135
7.2.1	Theory	135
7.2.1.1	Ideal Basin	135
7.2.1.2	Scour	135
7.2.2	Horizontal Velocity Control	137
7.2.2.1	Proportional Weir	137
7.2.2.2	Parshall Flume	138
7.2.2.3	Rectangular Section	142
7.2.2.4	Parabolic Section	146
7.2.3	Practice—Horizontal Flow Grit Chambers	147
7.2.3.1	Design and Performance—Examples	147
7.2.3.2	Removal Equipment	148

7.3	Aerated Grit Chambers.....	148
7.3.1	Principles of Aerated Grit Chamber Operation.....	150
7.3.2	Theory of Aerated Grit Chambers.....	150
7.3.2.1	Calculation of Grit Removal.....	150
7.3.2.2	Calculation of Spiral Length, DL	151
7.3.2.3	Empirical Guidelines.....	151
7.3.2.4	n Determination	151
7.3.2.5	Algorithm for Calculations	152
7.3.3	Practice: Aerated Grit Chambers.....	154
7.3.3.1	Guidelines from Five Designs	154
7.3.3.2	Summary of Guidelines	155
7.3.3.3	Pressure in Header Pipe.....	156
7.3.3.4	Blower Power	156
	Problems	157
	Acknowledgments	159
	Glossary	159
	References	160

Chapter 8	Flotation.....	163
8.1	Development of Flotation.....	163
8.1.1	Beginning Design Practice	163
8.1.2	Water and Wastewater Applications	163
8.2	DAF System Description.....	163
8.2.1	Synopsis of DAF Process.....	163
8.2.1.1	Coagulation	163
8.2.1.2	Flocculation.....	163
8.2.1.3	Contact Zone.....	163
8.2.1.4	Saturator.....	163
8.2.1.5	Gas Precipitation.....	164
8.2.1.6	Bubble–Floc Agglomerate	164
8.2.1.7	Float Layer.....	164
8.2.1.8	Clarified Water.....	164
8.2.1.9	Further Processing	164
8.3	Principles of DAF Flotation	164
8.3.1	Gas Transfer	164
8.3.1.1	Henry’s Law.....	164
8.3.1.2	Application of Henry’s Law to Saturator	166
8.3.1.3	Saturator.....	166
8.3.1.4	Gas Concentration at Nozzle Depth	167
8.3.1.5	Saturator Mass Balance	167
8.3.1.6	Saturator Packing.....	167
8.3.1.7	Hydraulic Grade Line	167
8.3.2	Gas Precipitation	168
8.3.2.1	Bubbles	168
8.3.2.2	Bubble Size	170
8.3.2.3	Bubble Size Distribution.....	170
8.3.2.4	Bubble Numbers	170
8.3.2.5	Nozzle Design.....	170
8.3.3	Contact Zone	171
8.3.3.1	Floc–Bubble Transport and Attachment.....	171
8.3.3.2	Bubble–Particle Contact	172
8.3.3.3	Parameter Values	172
8.3.4	Separation Zone.....	172
8.3.4.1	Rise Velocity of Bubbles.....	172

8.3.4.2	Rise Velocity of Particle–Bubble	172
8.3.4.3	Bubble–Particle Ratio	174
8.3.4.4	Concentration Expressions.....	174
8.3.5	Materials Balance for Dissolved Gas in Flotation Basin	178
8.3.5.1	Mass Balance for Flotation Basin.....	178
8.3.5.2	Mass Balance Calculations by Spreadsheet.....	179
8.4	Practice	180
8.4.1	Design Criteria.....	180
8.4.1.1	Flotation in Water Treatment.....	180
8.4.1.2	Flotation for Sludge Thickening.....	181
8.4.1.3	Air-to-Solids Ratio.....	181
8.4.2	Pilot Plants.....	181
8.4.2.1	Pilot Plant Study	181
8.4.3	Case: Birmingham.....	182
8.4.4	Equipment.....	183
	Problems	184
	Acknowledgments	186
	Glossary	186
	References	187

PART III Microscopic Particles

Chapter 9	Coagulation.....	191
9.1	Coagulation In-a-Nutshell.....	191
9.1.1	Defining Coagulation	191
9.1.1.1	Particles to Be Removed.....	191
9.1.1.2	Coagulation.....	191
9.1.1.3	Microflocs	191
9.1.1.4	Rapid-Mix	191
9.1.1.5	Flocculation.....	191
9.1.1.6	Themes of Coagulation Theory	191
9.1.2	Coagulation Practice.....	191
9.1.2.1	Dosage.....	191
9.1.2.2	Coagulation Effectiveness.....	192
9.2	Particles in Ambient Waters.....	192
9.2.1	Particle Variety	192
9.2.2	Particle Characteristics	192
9.2.2.1	Colloids.....	192
9.2.2.2	Microscopic Particles.....	192
9.2.2.3	Natural Organic Matter and Color.....	194
9.2.2.4	Total Organic Carbon	194
9.2.2.5	Turbidity	194
9.2.2.6	Particle Counts	194
9.2.3	Turbidity and Particle Counts in Ambient Waters and Finished Waters.....	194
9.2.3.1	Spatial Variation in Source Waters Compared with Plant Effluents.....	194
9.2.3.2	Seasonal Variation	194
9.3	Chemistry.....	194
9.3.1	Chemistry of Coagulation: Evolution of Theory and Practice	194
9.3.1.1	Key Innovations.....	195
9.3.1.2	Color	196
9.3.1.3	Modern Theory	196
9.3.2	Coagulation Reactions.....	197
9.3.2.1	Metal Ion Reactions with Water.....	197
9.3.2.2	Two Coagulation Mechanisms	197

	9.3.2.3	NOM Removal by Metal Coagulants	197
	9.3.2.4	Organics in Wastewaters	199
	9.3.2.5	Coagulation of Synthetic Organics	199
9.4		Double Layer Theory	200
	9.4.1	Double Layer Description	200
		9.4.1.1 Beginning	200
		9.4.1.2 Surface Charge	200
		9.4.1.3 Gouy–Chapman Model	200
		9.4.1.4 Fixed Layer	200
		9.4.1.5 Effect of Ionic Strength of Solution	200
		9.4.1.6 Electrostatic Potentials	201
		9.4.1.7 DLVO Theory	201
9.5		Trivalent Metal Ions: Reactions with Water	202
	9.5.1	Aluminum and Ferric Ions	203
		9.5.1.1 Waters of Hydration	203
		9.5.1.2 Expressing Concentrations	203
		9.5.1.3 Liquid Alum	204
	9.5.2	Alkalinity	204
		9.5.2.1 Role of Alkalinity as a Buffer	204
		9.5.2.2 Effect of Alkalinity on Demand for Alum	204
		9.5.2.3 Effect of Alum on pH	204
	9.5.3	Reactions between Alum/Ferric Iron and Water	205
		9.5.3.1 Beginning	205
		9.5.3.2 Sequential Hydrolysis Reactions	205
		9.5.3.3 Species Equilibrium	206
		9.5.3.4 Coagulation Zones	209
		9.5.3.5 Spreadsheet Construction of Coagulation Diagrams	209
		9.5.3.6 Polynuclear Species	210
		9.5.3.7 Summary of Alum Speciation	210
9.6		Synthetic Aluminum Polymers	210
	9.6.1	Characteristics of PACl	210
		9.6.1.1 Description of PACl	210
		9.6.1.2 Electrophoretic Mobility: Comparing Alum and PACl	210
9.7		Zeta Potential, Charge Density, and Streaming Current Potential	211
	9.7.1	Basic Notions of Electrophoretic Mobility	211
	9.7.2	Mathematical Relations for Electrophoresis	211
		9.7.2.1 Electrophoresis	211
		9.7.2.2 Zeta Potential	212
	9.7.3	Measured Zeta Potentials	214
		9.7.3.1 Typical Zeta Potentials	214
	9.7.4	Colloid Titration	215
	9.7.5	Streaming Current Monitor	215
9.8		Physical Models	216
	9.8.1	Jar Tests	216
	9.8.2	Bench Scale Filters	217
	9.8.3	Pilot Plants	218
		9.8.3.1 Independent Variables	218
		9.8.3.2 Dependent Variables	218
		9.8.3.3 Pilot Plant Design	218
9.9		Polymers	218
	9.9.1	Definitions	218
	9.9.2	Characteristics of Polymers	219
		9.9.2.1 Charge Concentration	219
		9.9.2.2 Specific Gravity	219
	9.9.3	Polymers in Wastewater Treatment	219
		9.9.3.1 Sludge Conditioning	219

9.9.4	Structure of Polymers	220
9.9.4.1	Functional Groups	220
9.9.4.2	Monomers	220
9.9.4.3	Polymers	221
9.9.5	Selection of Polymers	221
9.9.5.1	Polymer Screening	221
9.9.5.2	Polymer Packaging	223
9.9.5.3	Specification Sheets	224
9.9.5.4	Prepared Batches	224
9.9.5.5	Feed of Polymer	224
9.9.5.6	Concentration: Convention (Adapted from AWWA B453-96)	224
	Problems	226
	Acknowledgments	228
	Glossary	228
	References	235

Chapter 10 Mixing 239

10.1	Definitions and Applications	239
10.1.1	Definitions	239
10.1.1.1	Mixing	239
10.1.1.2	Near-Synonyms	239
10.1.2	Application Categories	239
10.1.2.1	Liquid–Solid	239
10.1.2.2	Liquid–Gas	239
10.1.2.3	Immiscible Liquids	239
10.1.2.4	Miscible Liquids	240
10.1.2.5	Fluid Motion	240
10.1.2.6	Pumping and Shear	240
10.1.2.7	Examples	240
10.1.3	Mixing as Rate Limiting	240
10.2	History of Mixing	240
10.2.1	Drinking Water Treatment	240
10.2.1.1	Initial Mixing	240
10.2.1.2	Gas Dissolution	241
10.2.2	Wastewater Treatment	241
10.2.3	Evolution of Mixing Theory	242
10.2.3.1	Development of Collision Frequency Mathematics	242
10.2.3.2	Derivation of G	243
10.2.3.3	Modifying Camp and Stein's G	243
10.2.3.4	Empirical Parameters	243
10.2.3.5	G and θ	243
10.2.4	Technologies of Mixing	244
10.3	Theory of Mixing	244
10.3.1	Transport Mechanisms	244
10.3.1.1	Advection	245
10.3.1.2	Turbulence	246
10.3.1.3	Transport Regime	252
10.3.2	Navier–Stokes Equation	253
10.3.2.1	Mathematics of Navier–Stokes Equation	253
10.3.2.2	Computational Fluid Dynamics	254
10.3.3	Similitude	254
10.3.3.1	Dimensionless Numbers	255
10.3.3.2	Variables of Impeller–Basin Mixing	256
10.3.3.3	Experimental Plots	256
10.3.3.4	Scale-Up by Fluid Similitude	256
10.3.3.5	Scale-Up Dilemma	258

10.3.4	Injection of Coagulant Chemicals	260
10.3.4.1	Disparity of Flows	260
10.3.4.2	Advection of Neat Alum	260
10.4	Mixing Technologies	261
10.4.1	Impeller Mixing	261
10.4.1.1	Reactors—Back-Mix and In-Line	261
10.4.1.2	Circulation Criterion for 0.99 Blending in a Back-Mix Reactor	262
10.4.1.3	Time Ratio, $t/Q(\text{reactor})$, to Attain 0.99 Blending—Experimental Procedure (a).....	264
10.4.1.4	Impeller Speed, $w(\text{impeller})$, to Attain 0.99 Blending—Experimental Procedure (b).....	264
10.4.1.5	Complete-Mix Reactors	264
10.4.2	Impellers and Tanks	266
10.4.2.1	Impeller Variety	266
10.4.2.2	Impeller Characteristics	266
10.4.2.3	Impeller Pumping.....	267
10.4.2.4	Tanks.....	269
10.4.2.5	Rushton System	270
10.4.2.6	In-Line Mixers	270
10.4.3	Jet Mixers	271
10.4.3.1	Flash Mixing by Submerged Jets	271
10.4.4	Static Mixers.....	276
10.4.4.1	General Principles	276
10.4.4.2	Baffles	276
10.4.4.3	Static Mixers	277
10.5	Summary	280
	Problems	280
	Acknowledgments	283
	Glossary	284
	References	288
	Bibliography	290

Chapter 11	Flocculation	291
11.1	Definitions.....	291
11.1.1	Floc	291
11.1.1.1	Biological Floc.....	291
11.1.1.2	Chemical Floc	291
11.1.1.3	Primary Particles	291
11.1.2	Flocculation	291
11.1.2.1	Orthokinetic Flocculation	291
11.1.2.2	Perikinetic Flocculation	291
11.1.2.3	Flocculent.....	291
11.2	Applications	292
11.2.1	Conventional Filtration.....	292
11.2.2	Direct Filtration	292
11.2.3	Flotation.....	292
11.2.4	Activated Sludge Floc Settling.....	292
11.2.5	Softening.....	292
11.2.6	Tertiary Treatment.....	292
11.3	History	292
11.3.1	Practice	292
11.3.1.1	Quiescent Basins.....	292
11.3.1.2	Langelier's Paddle Wheels.....	292
11.3.1.3	Design Guidelines	293
11.3.1.4	Flocculation Practice, c. 1940.....	294
11.3.2	Evolution of Theory	294
11.3.2.1	Langelier	294

11.3.2.2	Smoluchowski's Collision Equations	294
11.3.2.3	Camp's G	296
11.4	Theory of Flocculation	296
11.4.1	Kinetics.....	296
11.4.1.1	Frequency of Particle Collisions.....	296
11.4.1.2	Rate of Formation of New Particles, k	299
11.4.2	Nature of Flocs and Flocculation	299
11.4.2.1	Characteristics of Flocs.....	299
11.4.2.2	Floc Breakup.....	304
11.4.2.3	Bioflocculation	304
11.4.3	Flocculents.....	305
11.4.4	Design Principles for Paddle-Wheel Flocculators.....	306
11.4.4.1	Derivation of Camp's Equation for Paddle-Wheel Flocculation.....	306
11.4.4.2	P (paddle-wheel) with Units	308
11.5	Design.....	308
11.5.1	Design Procedure from Camp.....	308
11.5.1.1	Camp's Criteria	308
11.5.1.2	Camp's Guidelines	308
11.5.1.3	Spreadsheet Algorithm.....	310
11.5.2	Model Flocculation Basin	310
11.5.2.1	Calculations.....	310
11.5.2.2	Plots.....	310
11.5.2.3	Slip Factor.....	313
11.5.3	Plant Design	313
11.5.4	Other Technologies	315
11.5.4.1	Turbines	315
11.5.4.2	Baffles	315
11.6	Proprietary Technologies.....	319
11.6.1	Turbine Flocculators.....	320
11.6.2	Solids Contact Units.....	320
11.6.2.1	Principles.....	320
11.6.2.2	Design Practice, Equipment, Operation.....	321
11.6.3	Super-Pulsators [™]	321
11.6.4	Culligan Multi-Tech [™]	321
11.7	Summary.....	321
	Problems	321
	Acknowledgments	323
	Appendix 11.A: Derivation of Camp and Stein G for Three-Dimensional Cube	323
	Glossary	324
	References	326

Chapter 12 Rapid Filtration..... 329

12.1	Description of Rapid Filtration.....	329
12.1.1	Filtration Technology	329
12.1.1.1	In-a-Nutshell	329
12.1.1.2	Support Components.....	330
12.1.1.3	Filtration Mode	330
12.1.2	Applications.....	331
12.1.3	Variations.....	331
12.2	Development of Rapid Filtration.....	331
12.2.1	Development of Rapid Filtration.....	331
12.2.1.1	Hyatt Filter.....	331
12.2.1.2	Warren Filter.....	331
12.2.1.3	Other Proprietary Filters	331
12.2.1.4	Fuller's Experiments	332

12.2.2	Emergence of Filtration Practice	333
12.2.2.1	State of the Art, 1890 and 1990	334
12.2.2.2	Growth of Waterworks Industry	334
12.2.3	Progress in Filtration Practice	334
12.2.3.1	Dual Media	335
12.2.3.2	Breaking the HLR Barrier	335
12.2.3.3	Alternative Modes of Filtration	335
12.2.4	Modern Filtration Practice.....	335
12.2.4.1	The Federal Role.....	335
12.2.4.2	Modern Practice.....	335
12.3	Theory.....	336
12.3.1	Quest of Theory.....	336
12.3.1.1	Dependent Functions in Filtration	336
12.3.1.2	Definitions	336
12.3.2	Process Description	336
12.3.2.1	Experimental $C(Z)_t$ Results of Eliassen	336
12.3.2.2	Experimental $C(Z)_t$ Results of Ives.....	337
12.3.2.3	$C(Z, t)$ in Three Dimensions	337
12.3.2.4	Mass Transfer Similarities between Adsorption and Filtration	337
12.3.2.5	Relation between the $C(Z)_t$ Wave Front and the $C(t)_{Z=Z_0}$ Breakthrough Curve	337
12.3.2.6	Specific Solids Deposit, $\sigma(Z, t)$	339
12.3.2.7	Clogging Front.....	339
12.3.2.8	Local Hydraulic Gradient, $i(Z, t)$	340
12.3.2.9	Rational Design.....	341
12.3.2.10	Total Headloss and Components of Headloss	342
12.3.2.11	Characteristics of $C(t)_Z$ for a Filter Cycle	342
12.3.3	Mathematical Modeling.....	344
12.3.3.1	Iwasaki's Equations	344
12.3.3.2	Filter Coefficient	346
12.3.3.3	Transport Coefficient	346
12.3.3.4	Attachment Coefficient	349
12.3.3.5	Effect of Attachment Efficiency on Filter Ripening.....	349
12.3.3.6	Derivation of Materials Balance Expression	350
12.3.4	Synthesis of a Model.....	351
12.3.4.1	Solids Uptake Rate	351
12.3.4.2	Conditions at Equilibrium.....	352
12.3.4.3	Zones of Wave Front	353
12.3.5	Summary.....	353
12.4	Design.....	353
12.4.1	External Parameters	354
12.4.1.1	Design Decisions	354
12.4.1.2	Cost	354
12.4.2	Components of Filter Design	354
12.4.2.1	Layout of Filters	354
12.4.2.2	Hydraulic Modes of Filtration	355
12.4.2.3	Water Distribution	355
12.4.2.4	Media	356
12.4.2.5	Pipe Gallery	356
12.4.2.6	Clear-Well	358
12.4.2.7	Control Systems.....	359
12.4.3	Filter Box.....	359
12.4.3.1	Filtration Rate	359
12.4.3.2	Area of Filters	359
12.4.3.3	Net Water Production	359
12.4.3.4	Depth of Filter Box.....	359

12.4.4	Backwash.....	360
12.4.4.1	Manifold Principles.....	360
12.4.4.2	Types of Backwash Systems.....	361
12.4.4.3	Backwash Volume.....	362
12.4.4.4	Backwash Water Troughs.....	363
12.4.4.5	Under-Drain Systems.....	363
12.4.4.6	Bed Fluidization.....	365
12.4.4.7	Surface-Wash.....	368
12.4.4.8	Air-wash.....	369
12.4.4.9	Air-Water Concurrent Backwash.....	369
12.4.4.10	Collapse Pulsing.....	370
12.5	Operation.....	371
12.5.1	Filter Operating Cycle.....	372
12.5.2	Filtration Hydraulics.....	372
12.5.2.1	Clean-Bed Headloss.....	372
12.5.2.2	Progression of Headloss with Filter Run.....	373
12.5.2.3	Negative Pressure.....	374
12.5.2.4	Air Binding.....	374
12.5.3	Backwash.....	374
12.5.3.1	Mudballs and Surface Cracks.....	375
12.5.3.2	Floc-to-Grain Bonding.....	375
12.5.3.3	Practice.....	375
12.5.3.4	Operating Protocol.....	375
12.6	Pilot Plants.....	375
12.6.1	Equipment.....	376
12.6.1.1	Contaminant Injection.....	376
12.6.1.2	Filter Column.....	377
12.6.1.3	Pilot Plant System.....	378
12.6.1.4	Data Handling.....	378
12.7	Wastewater Filtration.....	378
12.7.1	Background.....	378
12.7.2	Forms of Practice.....	378
12.7.2.1	As a Unit Process within a Water Treatment Train.....	378
12.7.2.2	As a Stand-Alone Process Following Biological Treatment.....	378
12.8	Proprietary Equipment.....	379
12.8.1	Ancillary Equipment.....	379
12.8.2	Package Filtration Systems.....	379
12.8.2.1	Deep Bed Filtration—Parkson DynaSand®.....	379
12.8.2.2	Deep Bed Filtration—Culligan Multi-Tech®.....	380
12.8.2.3	Shallow Bed Filtration—ABW®.....	380
12.8.2.4	Package Filtration—EPD Wearnes USA®.....	380
12.8.3	Evaluation of Products.....	380
	Problems.....	381
	Acknowledgments.....	382
	Appendix 12.A: Filtration in New York.....	382
	Glossary.....	385
	References.....	391
Chapter 13	Slow Sand Filtration.....	395
13.1	Description.....	395
13.1.1	Slow Sand Technology.....	395
13.1.1.1	Filter Box and Appurtenances.....	395
13.1.1.2	Sand Bed.....	395
13.1.1.3	<i>Schmutzdecke</i>	395
13.1.1.4	Design Approach.....	395

13.1.2	Attributes	395
13.1.2.1	Selection Criteria.....	395
13.1.2.2	Effectiveness	395
13.1.2.3	Economy	396
13.1.2.4	Labor.....	396
13.1.2.5	Materials.....	397
13.1.2.6	Contextual Factors	397
13.1.3	History	397
13.1.3.1	James Simpson and the Start of Slow Sand.....	398
13.1.3.2	Evolution of Practice	398
13.2	Slow Sand as a Process	399
13.2.1	Removal Mechanisms	399
13.2.1.1	<i>Schmutzdecke</i> and Its Role in Straining	399
13.2.1.2	Depth Filtration	400
13.2.2	Hydraulics.....	401
13.2.2.1	Darcy's Law	401
13.2.2.2	Intrinsic Hydraulic Conductivity.....	401
13.2.2.3	Hydraulic Profile and Headloss	403
13.3	Design	403
13.3.1	Filter Box.....	404
13.3.1.1	Hydraulic Loading Rate and Area.....	404
13.3.1.2	Number of Cells.....	405
13.3.1.3	Layout	405
13.3.1.4	Depth of Box	405
13.3.1.5	Structural Design	406
13.3.2	Hydraulics.....	406
13.3.2.1	Backfilling after Scraping	407
13.3.2.2	Air Binding	408
13.3.2.3	Distribution of Raw Water Inflow Kinetic Energy	408
13.3.2.4	Drainage System	408
13.3.2.5	Underdrain Manifold Design.....	408
13.3.2.6	Depth of Sand	408
13.3.2.7	Sand Size	409
13.3.2.8	Gravel Support	410
13.3.3	Support Systems	411
13.3.3.1	Flow Measurements	411
13.3.3.2	Piezometers	411
13.3.3.3	Turbidimeters	411
13.3.3.4	Flow Control.....	411
13.3.3.5	Tailwater Control.....	411
13.3.3.6	Pipe Gallery	412
13.3.3.7	Access to Filters.....	412
13.3.3.8	Plumbing Functions	412
13.3.3.9	Hydraulic Profile.....	412
13.3.3.10	Headroom.....	412
13.3.3.11	Designing to Avoid Freezing.....	412
13.3.3.12	Sand Recovery System	413
13.4	Pilot Plant Studies.....	413
13.4.1	Pilot Plant Construction.....	414
13.4.2	Case Study.....	414
13.4.2.1	Context.....	414
13.4.2.2	Pilot Plant Setup	414
13.4.2.3	Results.....	415
13.4.2.4	Discussion	415

13.5	Operation	415
13.5.1	Plant Start-Up	415
13.5.2	Operating Tasks	415
13.5.2.1	Scraping	415
13.5.2.2	Rebuilding the Sand Bed	416
13.5.3	Monitoring and Reporting	416
	Problems	416
	Acknowledgments	418
	Glossary	418
	References	420

Chapter 14 Cake Filtration

14.1	Description	423
14.1.1	Cake Filtration In-a-Nutshell	423
14.1.1.1	Applications	423
14.1.1.2	Definitions	423
14.1.1.3	Phases of Operation	424
14.1.1.4	Process Description	424
14.1.1.5	DE Selection	424
14.1.2	Media	425
14.1.2.1	Kinds of Media	425
14.1.2.2	Sources of Media	425
14.1.2.3	Manufacturing of Media	426
14.1.2.4	Characteristics of Media	427
14.1.3	Attributes	427
14.1.4	History	428
14.1.4.1	1940s' Military Use of DE Filtration	428
14.1.4.2	1950s' Adaptation of DE for Municipal Use	429
14.1.4.3	Research	430
14.2	Cake Filtration Process	431
14.2.1	Particle Removal Effectiveness	431
14.2.1.1	Turbidity and Bacteria	431
14.2.1.2	Particle Counts	432
14.2.1.3	Iron and Manganese	432
14.2.1.4	Asbestiform Fibers	432
14.2.1.5	Biological Particles	432
14.2.2	Removal Mechanisms	433
14.2.2.1	Straining and Embedding	433
14.2.2.2	The Role of Body Feed	433
14.2.2.3	Adsorption	433
14.2.2.4	Comparisons between Filtration Processes	433
14.2.3	Hydraulics	433
14.2.3.1	Hydraulics of Cake Filtration	434
14.3	Design	437
14.3.1	Diatomite Technologies	437
14.3.1.1	Equipment	438
14.3.1.2	System Components	439
14.3.1.3	Layout	440
14.3.2	Design Parameters	441
14.3.2.1	Variables	441
14.3.2.2	Guidelines and Criteria	441
14.3.3	Design Examples	442
14.3.3.1	Data from 12 Plants	442
14.3.3.2	Plant Descriptions	442
14.4	Operation	445
14.4.1	Operating Protocol	445

14.4.1.1	Pre-Coat Deposit.....	445
14.4.1.2	Body Feed.....	446
14.4.1.3	Valve and Pump Operation	446
14.4.2	Monitoring.....	446
14.4.2.1	Flow versus Time	447
14.4.2.2	Headloss versus Time.....	447
14.4.2.3	Turbidity versus Time.....	447
14.4.2.4	Criteria for Run Termination	447
14.4.3	Cleaning and Start-Up.....	447
14.4.3.1	Protocol.....	447
14.4.3.2	Start-Up.....	447
14.4.4	Disposal of Waste Diatomite.....	447
14.4.4.1	Waste Storage	447
14.4.4.2	Waste Disposal	447
14.5	Pilot Plant Studies.....	447
14.5.1	Questions for a Pilot Plant Study	447
14.5.1.1	Functional Relationships.....	448
14.5.2	Cases.....	448
14.5.2.1	SR Ranch, Colorado	448
14.5.2.2	100 Mile House, British Columbia.....	449
	Problems	450
	Acknowledgments	450
	Glossary	451
	References	453

PART IV *Molecules and Ions*

Chapter 15	Adsorption.....	457
15.1	Description.....	457
15.1.1	Adsorption In-a-Nutshell.....	457
15.1.1.1	Definitions.....	457
15.1.1.2	Process Description.....	458
15.1.1.3	Operation.....	458
15.1.1.4	Performance Measures	458
15.1.2	Adsorbents.....	458
15.1.2.1	Kinds of Adsorbents	458
15.1.2.2	Sources of Activated Carbon.....	459
15.1.2.3	Manufacturing of Activated Carbon.....	459
15.1.2.4	Characteristics of GAC.....	459
15.1.2.5	Shipping Data	463
15.1.3	Adsorbates	463
15.1.3.1	Organic Compounds	463
15.1.3.2	Natural Organic Matter	464
15.1.4	Applications.....	464
15.1.5	History	464
15.1.5.1	Lore	465
15.1.5.2	Science	465
15.1.5.3	Practice.....	465
15.2	Adsorption Process Theory	466
15.2.1	Equilibrium.....	466
15.2.1.1	Reaction	466
15.2.1.2	Langmuir Isotherm.....	466
15.2.1.3	Freundlich Isotherm	469
15.2.1.4	General Isotherm.....	470
15.2.1.5	Multicomponent Equilibria	470

15.2.2	Kinetics.....	471
15.2.2.1	Graphical Depiction.....	471
15.2.2.2	Rate of Uptake: Theoretical.....	473
15.2.2.3	Empirical Rate Equation.....	473
15.2.3	Reactor Theory for Packed Beds.....	473
15.2.3.1	Mathematics.....	473
15.2.3.2	Advection Kinetics.....	474
15.2.3.3	Simulation Modeling.....	476
15.2.3.4	Characteristics of Output Curves.....	477
15.2.4	Rational Design.....	479
15.2.4.1	Quick-and-Dirty Mass Balance.....	480
15.2.4.2	Empirical Data for L_{wf} and v_{wf}	481
15.2.4.3	Theoretical Results for L_{wf} and v_{wf}	481
15.2.5	Problems.....	481
15.2.5.1	Competition between Adsorbents.....	481
15.2.5.2	Chromatographic Effect.....	482
15.2.5.3	Bacterial Colonization.....	482
15.3	Laboratory and Pilot Plant Studies.....	483
15.3.1	Questions for a Laboratory/Pilot Plant Study.....	483
15.3.1.1	Isotherm Determination.....	483
15.3.1.2	Determine v (wave front).....	483
15.3.1.3	L (wave front).....	484
15.3.1.4	Breakthrough Curve.....	484
15.3.1.5	Rate of Headloss Increase.....	484
15.3.1.6	Backwash Velocity.....	484
15.3.1.7	Assess Competitive Effects of Different Adsorbates.....	484
15.3.1.8	Discover Effects of Unanticipated Problems.....	484
15.3.1.9	Fabrication.....	484
15.3.2	Demonstration-Scale Plants.....	484
15.3.2.1	Pomona.....	484
15.3.2.2	Denver Reuse Plant.....	485
15.4	Design.....	486
15.4.1	Design Variables.....	486
15.4.1.1	Independent Process Variables.....	486
15.4.1.2	Guidelines and Criteria.....	488
15.4.2	Design Protocol.....	489
15.4.2.1	Spreadsheet Layout.....	489
15.4.2.2	Spreadsheet Scenarios.....	490
15.4.3	Design Examples.....	490
15.4.3.1	Examples of Sites.....	490
15.4.3.2	GAC for Taste-and-Odor Control.....	490
15.4.3.3	Chemicals in Drinking Water Sources.....	490
15.4.3.4	Pump and Treat.....	492
15.4.3.5	Tertiary Treatment.....	494
15.5	Operation and Costs.....	496
15.5.1	Operation Characteristics.....	496
15.5.2	Costs.....	496
15.5.2.1	South Lake Tahoe.....	496
15.5.2.2	Virgin GAC.....	496
15.5.2.3	Regeneration.....	496
	Problems.....	497
	Acknowledgments.....	499
	Appendix 15.A: Freundlich Isotherm Coefficients.....	499
	Glossary.....	499
	References.....	507
	Further Readings.....	510

Chapter 16 Ion-Exchange	511
16.1 Description	511
16.1.1 Ion-Exchange In-a-Nutshell	511
16.1.1.1 Definitions	511
16.1.1.2 Process Description	511
16.1.1.3 Phases of Operation	511
16.1.2 History	512
16.1.2.1 Science	512
16.1.3 Applications	512
16.1.3.1 Municipal Use	512
16.1.3.2 Removals of Specific Ions	513
16.1.3.3 Deionization	513
16.1.4 Media	513
16.1.4.1 Mineral Ion-Exchangers	513
16.1.4.2 Clays	513
16.1.4.3 Zeolites	513
16.1.4.4 Synthetic Resins	516
16.1.4.5 Aluminas	519
16.2 Ion-Exchange Theory	520
16.2.1 Capacity of Media	520
16.2.1.1 Expressions of Capacity	520
16.2.1.2 Upper Limit of Capacity	520
16.2.2 Equilibria	521
16.2.2.1 General Reaction and Equilibrium Equations	521
16.2.2.2 Isotherm Expression of Equilibrium	521
16.2.2.3 Selectivity of Counterions	521
16.2.3 Kinetics	522
16.2.3.1 Rate-Determining Step	522
16.2.3.2 Fick's First Law	522
16.3 Design	523
16.3.1 Selection of Ion-Exchangers	523
16.3.1.1 Resins	523
16.3.1.2 Zeolites	523
16.3.1.3 Range of Ion-Exchangers and Properties	523
16.3.2 System Design	524
16.3.2.1 Pretreatment	524
16.3.2.2 Reactor Cycle	524
16.3.2.3 Regeneration	525
16.3.3 Reactor Design	525
16.3.3.1 Summary of Design Data	525
16.3.3.2 Pilot Plant Studies	526
16.4 Operation	526
16.4.1 Operating Cycle	527
16.4.1.1 Production	527
16.4.1.2 Regeneration	527
16.4.1.3 Disposal	527
16.5 Case Studies	527
16.5.1 Nitrate Removal at Glendale, Arizona	527
Problems	528
Acknowledgments	529
Appendix 16.A: Ion-Exchange Conversions	529
Glossary	532
References	537
Bibliography	538

Chapter 17	Membrane Processes	539
17.1	Description	539
17.1.1	Membranes In-a-Nutshell	539
17.1.1.1	Analysis: Flow Balance Principle	539
17.1.1.2	Definitions	539
17.1.1.3	Acronyms for Membrane Materials and Membranes	539
17.1.1.4	Process Description	539
17.1.1.5	Membrane Technology	540
17.1.1.6	Racks	541
17.1.1.7	Treatment Train	541
17.1.1.8	Operation	541
17.1.2	Global Capacity	542
17.1.3	Membrane Types	542
17.1.4	Membrane Materials	543
17.1.5	Membrane Structure	543
17.1.5.1	Microporous Membranes	543
17.1.5.2	Asymmetric Membranes	543
17.1.6	Manufacturing	544
17.1.6.1	Flat Sheets	544
17.1.6.2	Tubes	544
17.1.7	Packaging	545
17.1.7.1	Plate-and-Frame Modules	545
17.1.7.2	Spiral-Wound Membrane Modules	545
17.1.7.3	Hollow-Fiber Modules	545
17.1.7.4	Flow within Membrane Element	547
17.1.7.5	Ratings	547
17.1.7.6	Variations in Manufacturer's Products	548
17.1.8	Applications	548
17.1.8.1	Particle Removals	549
17.1.8.2	Removal of Organics	549
17.1.8.3	Removal of Cations and Anions	549
17.1.9	Pros and Cons	549
17.1.9.1	Advantages	549
17.1.9.2	Disadvantages	549
17.2	History	549
17.2.1	Membranes in Science	549
17.2.1.1	Beginnings	550
17.2.1.2	The Development Period	550
17.2.1.3	Modern Period	550
17.2.2	Membranes in Water Treatment Practice	550
17.3	Theory	550
17.3.1	Performance Variables	550
17.3.2	Solute/Particle Rejection	550
17.3.3	Models Describing Water and Solute Flux through Membranes	551
17.3.4	Basic Notions for a Cross-Flow Membrane Element	551
17.3.4.1	Flow Balance	551
17.3.4.2	Mass Balance and Pressures	552
17.3.4.3	Water Flux Density	552
17.3.4.4	Solute Mass Flux	552
17.3.4.5	Transmembrane Pressure	552
17.3.5	Poiseuille Law	552
17.3.6	Osmosis	554
17.3.6.1	Osmotic Pressure	554
17.3.6.2	Reverse Osmosis	554
17.3.6.3	Effect of Membrane Pressure on Water Flux Density	555

17.3.7	Electrodialysis.....	556
17.3.7.1	Applications	556
17.3.8	Fouling.....	556
17.3.8.1	Reversible and Irreversible Fouling.....	557
17.3.8.2	Natural Organic Matter	557
17.3.8.3	Particle Fouling	557
17.3.8.4	Inorganics.....	557
17.3.8.5	Concentration Polarization.....	557
17.4	Design	559
17.4.1	Pretreatment.....	559
17.4.1.1	Cartridge Filters	559
17.4.1.2	Microfilter	559
17.4.1.3	Conventional Treatment.....	559
17.4.1.4	Other Pretreatment	559
17.4.2	Membrane Layouts.....	559
17.4.2.1	First Stage	560
17.4.2.2	Second Stage.....	560
17.4.2.3	Third Stage.....	560
17.4.2.4	Concentrate	560
17.4.2.5	Recoveries	560
17.5	Operation	560
17.5.1	Integrity Testing	561
17.5.1.1	Breaches.....	561
17.5.1.2	Testing.....	561
17.5.2	Cleaning.....	561
17.6	Pilot Plants.....	561
17.6.1	Utility of Pilot Plants.....	561
17.6.1.1	Pilot Plant Design	561
17.6.1.2	Pilot Plant Operation.....	562
17.7	Case	562
17.7.1	City of Brighton Reverse Osmosis Water Treatment Plant	562
17.7.1.1	Background	562
17.7.1.2	Brighton Pilot Plant	562
17.7.1.3	Design Parameters	562
17.7.1.4	Plant Layout.....	563
	Problems	564
	Acknowledgments	565
	Glossary	565
	References	569

Chapter 18 Gas Transfer 571

18.1	Description.....	571
18.1.1	Gas Transfer In-a-Nutshell	571
18.1.1.1	Comparison with Other Mass-Transfer Processes.....	571
18.1.1.2	Process Description.....	571
18.1.2	Applications.....	571
18.1.3	History	571
18.1.3.1	Theory	572
18.1.3.2	Stream Aeration	572
18.1.3.3	Oxygen Transfer in Activated Sludge	572
18.1.3.4	Spiral Flow Diffusers.....	572
18.1.3.5	Turbine Aeration.....	572
18.1.3.6	Grid Diffusers	573
18.1.3.7	Air Stripping	573

18.2	Gas Transfer Theory	573
18.2.1	Equilibria	573
18.2.1.1	Henry's Law	573
18.2.2	Kinetics	573
18.2.2.1	Diffusion	573
18.2.2.2	Adaptation of Fick's Law to Two-Film Theory	575
18.2.2.3	Surface Renewal Models	579
18.2.2.4	$K_L a$ as a Design Parameter	580
18.2.2.5	Derivation of Working Equation	580
18.2.3	Reactor Modeling	583
18.2.3.1	Continuous-Flow Complete-Mix Reactor Modeling for Gas Transfer	583
18.2.3.2	Batch Reactor Aeration Modeling	584
18.2.3.3	Column Reactor Modeling	585
18.2.3.4	Column Reactor Modeling: Packed Beds	588
18.2.3.5	Effect of Gas on $K_L a$ and Uptake/Stripping Effects	588
18.3	Design	589
18.3.1	Aerator Design	589
18.3.1.1	Algorithm for Aerator Sizing	589
18.3.1.2	Oxygen Transferred per Unit of Energy Expenditure	591
18.3.2	Equipment	591
18.3.2.1	Reactor Types	592
18.3.2.2	Turbine Aerators	592
18.3.2.3	Diffused Aeration	594
18.3.3	Operation	597
18.4	Case Studies	597
18.4.1	Fine-Bubble Diffusers	597
18.4.2	Air Stripping	597
18.4.2.1	Sydney Mine at Valrico, Florida	597
18.4.2.2	Well 12A: City of Tacoma, Washington	597
18.4.2.3	Wurtsmith AFB: Oscoda, Miami	599
18.4.2.4	Hyde Park Superfund Site, New York	599
	Problems	599
	Acknowledgments	601
	Appendix 18.A: Onda Coefficients	602
	18.A.1 Onda Correlations	602
	18.A.2 Onda Equations	602
	Glossary	603
	References	604

Chapter 19	Disinfection	607
19.1	Fundamentals	607
19.1.1	Microorganisms and Diseases	607
19.1.2	Disinfectants	607
19.2	History	607
19.2.1	Chlorine	607
19.2.1.1	Story of Chlorine	607
19.2.1.2	Disinfection Byproducts Issue	610
19.2.2	Ozone	610
19.2.3	Chlorine Dioxide	611
19.2.4	Ultraviolet Radiation	611
19.2.5	Other Disinfectants	612
19.2.5.1	Iodine	612
19.2.5.2	Bromine	612
19.2.5.3	Silver	612

19.3	Theory	612
19.3.1	Inactivation	613
19.3.1.1	Factors	613
19.3.1.2	Mathematics	613
19.3.1.3	Ct 's Compiled	614
19.3.1.4	Ct (chlorine) for <i>Giardia lamblia</i> Cysts	614
19.3.1.5	Inactivation by Ozone	614
19.3.2	Application of Chick–Watson Relation	614
19.3.2.1	Examples of $C \cdot t$ Relation	617
19.3.3	Chlorine Chemistry	617
19.3.3.1	Chlorine Properties	617
19.3.3.2	Chlorine Demand	618
19.3.4	Chloramines	622
19.3.4.1	Chlorine–Ammonia Reactions	622
19.3.4.2	Chloramine Disinfection	622
19.3.5	Ozone Chemistry	622
19.3.6	Chlorine Dioxide	622
19.3.6.1	Effectiveness of Chlorine Dioxide as a Disinfectant	622
19.3.6.2	Characteristics of ClO_2	623
19.3.6.3	Reaction Alternatives	623
19.3.7	Ultraviolet Radiation	624
19.3.7.1	Disinfection Rate by UV	624
19.3.7.2	Log R 's by UV	625
19.3.7.3	Radiation Fundamentals	625
19.3.7.4	Reactor Design	628
19.4	Design	629
19.4.1	Chlorine	629
19.4.1.1	Chlorine Feed	629
19.4.1.2	Reactor Design	630
19.4.2	Hypochlorite	630
19.4.3	Ozone	630
19.4.4	Chlorine Dioxides	631
19.4.5	UV Reactors	631
19.4.5.1	Hydraulics	631
19.4.5.2	UV Reactors Volume	631
19.4.5.3	UV Lamps	632
19.4.5.4	Lamp Components	632
19.4.5.5	UV Design Guidelines	633
19.4.6	Costs	633
19.4.7	Case	633
19.4.8	Summary	633
19.5	Operation	633
19.5.1	Chlorine Operation	633
19.5.2	Ozone Operation	633
19.5.3	Ultraviolet Lamps	634
	Problems	634
	Acknowledgments	635
	Glossary	635
	References	640
Chapter 20	Oxidation	643
20.1	Description	643
20.1.1	Applications of Oxidation Technology	643
20.1.2	History of Oxidation Technology	643
20.1.2.1	Oxidation Based on Electromotive Potential	643

20.1.2.2	Wet-Oxidation.....	644
20.1.2.3	Supercritical Water Oxidation	644
20.2	Oxidation Theory.....	644
20.2.1	Fundamentals.....	644
20.2.1.1	Definitions.....	645
20.2.1.2	Enumeration of Reaction	645
20.2.1.3	Half Reactions.....	645
20.2.1.4	Oxidation Numbers.....	646
20.2.1.5	Thermodynamic Relations	646
20.2.2	Oxidants.....	647
20.2.2.1	Chlorine.....	647
20.2.2.2	Ozone	647
20.2.2.3	Hydroxyl Radical.....	649
20.2.2.4	Permanganate	649
20.2.2.5	Chlorine Dioxide.....	649
20.2.2.6	Titanium Dioxide.....	650
20.2.3	Supercritical Water Oxidation	650
20.2.3.1	Critical Point.....	650
20.2.3.2	SCWO In-a-Nutshell.....	650
20.2.3.3	Characteristics of Supercritical Water Relevant to Engineering	651
20.2.3.4	Supercritical Reactors	652
20.2.3.5	Research in the 1990s.....	653
20.2.3.6	Design Factors	653
20.2.3.7	Case Study: SCWO of Pulp and Paper Mill Sludge	653
20.3	Practice	655
	Problems	655
	Acknowledgments	656
	Glossary	656
	References	658
	Further Reading.....	659

Chapter 21	Precipitation.....	661
21.1	Description.....	661
21.1.1	Precipitation In-a-Nutshell.....	661
21.1.1.1	Definitions	661
21.1.1.2	Comparison with Other Processes	661
21.1.1.3	Process Description.....	661
21.1.2	Applications.....	661
21.1.2.1	Softening	661
21.1.2.2	Toxic Metals Removal.....	662
21.1.3	History	662
21.1.3.1	Softening	662
21.1.3.2	Sewage Treatment.....	662
21.1.3.3	Heavy Metals	662
21.2	Precipitation Theory	663
21.2.1	Equilibria	663
21.2.1.1	Solubility Law.....	663
21.2.1.2	Application of Solubility Law	663
21.2.1.3	Listing of Solubility Products.....	665
21.2.1.4	Solubility pC–pH Diagrams	665
21.2.1.5	pe–pH Diagrams	666
21.2.1.6	General Rules of Solubility	667
21.2.2	Hardness	667
21.2.2.1	Occurrence of Hardness.....	667
21.2.2.2	Expressing of Hardness as CaCO ₃	667
21.2.2.3	Other Definitions of Hardness	668

21.2.2.4	Softening Reactions	668
21.2.2.5	Lime-Soda Process.....	669
21.2.3	Chemistry of Metals	669
21.3	Practice	670
21.3.1	Lime Softening.....	670
21.3.2	Precipitation of Heavy Metals.....	670
21.3.2.1	Common Chemical Reactions	670
21.3.2.2	Case: Mine Drainage	671
21.3.3	Precipitation of Anions.....	671
21.3.3.1	Phosphate Precipitation.....	671
21.3.3.2	Cyanide Precipitation.....	672
Problems	.....	672
Acknowledgment	.....	672
Glossary	.....	672
References	.....	675

PART V *Biological Treatment*

Chapter 22	Biological Processes and Kinetics.....	679
22.1	Background.....	679
22.1.1	1880–1980.....	679
22.1.2	Practice	679
22.1.3	Theory.....	679
22.1.4	Definitions	680
22.1.4.1	Reaction Classifications.....	680
22.1.4.2	BOD Nomenclature	681
22.1.4.3	Surrogates for Active Biomass Concentration, X	681
22.1.5	Wastewaters.....	681
22.1.5.1	Municipal Wastewaters.....	681
22.1.5.2	Industrial Wastes.....	681
22.1.5.3	Contaminants	683
22.2	Cell Metabolism	683
22.2.1	Metabolic Reactions	684
22.2.1.1	Catabolism	684
22.2.1.2	Anabolism	685
22.2.1.3	Cell Division.....	686
22.2.1.4	Photosynthesis.....	686
22.2.1.5	Energy Principles.....	686
22.3	Biological Treatment Overview	687
22.3.1	Composition of Substrates.....	687
22.3.1.1	Domestic Wastewater and Organic Compounds.....	687
22.3.1.2	Industrial Wastewaters	688
22.3.2	Composition of Cells.....	688
22.3.2.1	Empirical Formulae for Cells	688
22.3.3	Biological Reactions.....	688
22.3.3.1	Substrate to Cells	688
22.3.3.2	Heterotrophic	689
22.3.3.3	Autotrophic Involving Nitrogen	689
22.3.3.4	Anaerobic.....	690
22.3.3.5	Balancing Equations by Half-Reactions.....	691
22.4	Cell Yield.....	692
22.4.1	Cell-Yield Calculation.....	692
22.4.2	Cell Maintenance and Endogenous Respiration	693

22.4.2.1	Cell Maintenance	693
22.4.2.2	Endogenous Respiration	693
22.4.2.3	Microbial Growth Curve and Debris Accumulation	694
22.4.3	Net Cell Yield, $Y(\text{net})$	694
22.4.3.1	Cell Mass Relations	694
22.4.3.2	Cell Mass Rate Relations.....	694
22.4.4	Decline in Degradable VSS	695
22.4.5	Cell-Yield Data.....	695
22.5	Kinetics of Biological Reactions	695
22.5.1	Monod Description of Biological Reactions.....	695
22.5.2	K_s as the Half-Saturation Constant.....	695
22.5.3	Net Specific Growth Rate, $\mu(\text{net})$	696
22.5.4	Temperature Effect	697
22.5.5	Evaluation of Kinetic Constants.....	697
22.5.5.1	Data on Kinetic Constants	697
22.5.6	Andrews/Haldane Model of Substrate Inhibition	697
22.5.7	Kinetic Parameters.....	698
22.5.7.1	Specific Substrate Utilization Rate, U	698
22.5.7.2	F/M Ratio	700
22.5.7.3	Conversion F/M to U	700
22.5.7.4	Relating Monod Kinetics to U	701
22.5.7.5	Sludge Age, θ_c	701
22.5.7.6	Minimum Cell Regeneration Time, θ_c^m	701
22.5.7.7	Relationship between U and θ_c	701
22.5.8	Nitrification/Denitrification	701
22.5.8.1	Nitrification: NH_4^+ to NO_3^-	701
22.5.8.2	Denitrification: NO_3^- to N_2 Gas	702
22.5.9	Phosphorous Uptake.....	702
22.5.9.1	Occurrence in Wastewaters.....	702
22.5.9.2	Uptake to Cells	702
22.5.9.3	Theory	702
22.5.9.4	Technologies	703
22.6	Summary	703
	Problems	703
	Acknowledgments	704
	Appendix 22.A: Proteins	704
22.A.1	Protein Molecules	704
22.A.2	Urea	705
22.A.3	ATP	705
	Appendix 22.B: Michaelis–Menten Equation	705
22.B.1	Enzyme Kinetics.....	705
	Glossary	707
	References	718

Chapter 23 Biological Reactors 721

23.1	Biological Reactor Spectrum.....	721
23.2	Activated Sludge.....	721
23.2.1	History	721
23.2.1.1	Beginnings	721
23.2.1.2	From Empiricism to Science	724
23.2.1.3	Milestones	724
23.2.1.4	Modern History	725
23.2.2	Activated-Sludge Reactor Analysis.....	725
23.2.2.1	Materials Balance.....	726
23.2.2.2	Conventional Activated Sludge	727
23.2.2.3	Extended Aeration	729

23.2.2.4	Aerated Lagoon.....	729
23.2.2.5	Plug-Flow Reactor	730
23.2.3	Numerical Modeling.....	732
23.2.3.1	Numerical Model Concept.....	733
23.2.3.2	IWA Activated-Sludge Model	733
23.2.4	Practice	733
23.2.4.1	Empirical Guidelines.....	734
23.2.4.2	Experience with Plants.....	737
23.2.5	Operation	737
23.2.5.1	Bulking Sludge	738
23.3	Biofilm Reactors	739
23.3.1	Biofilms	739
23.3.1.1	Structure.....	739
23.3.1.2	Transport of Nutrients.....	739
23.3.2	Biofilm Reactors Model	739
23.3.2.1	Empirical Equation	739
23.3.2.2	Trickling-Filter Spreadsheet Model	741
23.4	Anaerobic Reactors.....	741
23.4.1	Evolution of Separate Sludge Digestion	741
23.4.2	Design Criteria.....	742
23.4.2.1	High-Rate Digestion	742
23.4.3	Process Design Principles	742
23.4.3.1	Reactions.....	743
23.4.3.2	Kinetics	744
23.4.3.3	Influences on Reaction Velocity.....	744
23.4.3.4	Effect of Temperature.....	745
23.4.3.5	Mixing.....	745
23.4.3.6	Environmental Conditions	746
23.4.3.7	Materials Balance: Kinetic Model	746
23.4.3.8	Practice.....	746
23.4.4	Operation and Monitoring.....	747
23.4.4.1	Process Upsets	747
23.4.4.2	Indicators and Tests	747
23.4.4.3	Percent Reduction of Volatile Suspended Solids	747
23.5	Summary	748
23.5.1	State of the Art.....	748
23.5.2	Parameters	748
	Problems	749
	Activated Sludge.....	749
	Bio-Filters	750
	Anaerobic.....	750
	Acknowledgments	751
	Appendix 23.A: Biofilm Reactor Model.....	751
23.A.1	Biofilm Reactors Model	751
23.A.1.1	Mathematics	752
23.A.1.2	Approximation Model by “Lumping” Coefficients.....	753
	Glossary	754
	References	754
	Pre-Appendix Tables	757
	Appendix A International System of Units.....	765
	Appendix B Physical Constants and Physical Data.....	773

Appendix C	Miscellaneous Relations.....	783
Appendix D	Fluid Mechanics—Reviews of Selected Topics	791
Appendix E	Porous Media Hydraulics	819
Appendix F	Alum Data and Conversions.....	833
Appendix G	Dimensionless Numbers.....	847
Appendix H	Dissolved Gases	851
Index	.....	871

Preface

This book is intended primarily as a text for a course in water treatment normally taught to seniors or first-year graduate students. The academic background needed includes the basic undergraduate courses in engineering, that is, mathematics, general chemistry, and fluid mechanics.

The main thrust of the book was to delineate principles that support practice. The “unit processes” approach was the organizing concept. Most of the principles identified are common to any kind of water treatment, for example, drinking water, municipal wastewater, industrial water, industrial wastewater, and hazardous wastewater. The book seeks to identify the strands of theory rather than to keep up with the latest technologies. The underlying idea was that technologies change but principles remain constant.

The chapters are sprinkled with boxes which are explanatory asides. The idea of the boxes was to enlarge the reader’s perspective of a topic by including some of the lore and history. Understanding how we arrived at our present state of the art places it in a more logical context. The book intends not only to provide technical proficiency but also to add insight and understanding of the broader aspects of water

treatment unit processes. As a note, boxes of living persons were not included without their respective verbal permissions. In writing biography boxes, I did not consider persons who were of my generation or younger, albeit I know many who would warrant such consideration, but perhaps from a younger writer.

The book is organized as follows: Parts I through IV (Chapters 1 through 21) are distillations of *Water Treatment Unit Processes—Physical and Chemical* (CRC Press, Boca Raton, FL, 2006). Part V (Chapters 22 and 23 and on biological treatment) was developed for this book. The intent was to abstract key principles of unit processes with minimal amplification. The 2006 book is more comprehensive, with additional theory and examples of practice. Problems are intended to illustrate principles, but with regard to practice. The SI (kg-m-s) system of units has been used; other metric units have been used as needed. The equivalent U.S. customary units are shown in most tables and figures.

David Hendricks

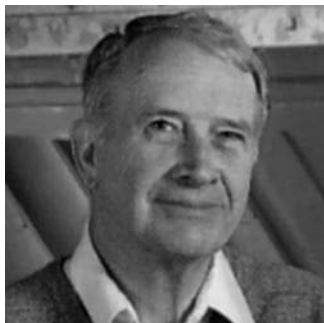
Acknowledgments

Acknowledgments have been included at the end of most chapters. A number of persons have shown interest in the book and have helped in various ways. Kevin Gertig, manager of water resources and treatment operations, Fort Collins Utilities, has supported the idea of the book and has provided advice and help when needed. Other friends and colleagues in the industry have provided help whenever required.

From the publisher's side, Joseph Clements, editor, Taylor & Francis, CRC Press, Boca Raton, Florida, has nurtured the book during the three years of its development along with

Jessica Vakili, production editor. Shayna Murry was the graphic designer for the cover art. Andrea Dale compiled information about the book for dissemination. Robert Sims was the project editor and saw the book through its final stages. Perundevi Dhandapani, project manager, oversaw the copyediting of the text, finding many of the author's oversights and also ways to improve the book's readability. In summary, the manuscript was transformed to a book through the work of the professionals at Taylor & Francis/CRC Press.

Author



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Downloadable Files

Spreadsheet tables have been included as a means to illustrate applications of design principles that involve computations. They are intended as supplemental material for the reader to modify as may be useful.

The spreadsheets are referenced in the text by a “CD” prefix. For example, “Table CD4.3” in the text indicates that the table is found in spreadsheet form in a file with that designation. In the text, “Table CD4.3” is found as an excerpt from the spreadsheet. The excerpt permits the reader to glean the gist of the spreadsheet contents but without the imperative to access it (except as convenient). The “CD” prefix has no

current significance except as a way to designate the respective content as being a computer “file.”

Some 60 spreadsheets were generated for this text and are available from the CRC Web site. They are listed in the following “*Contents–Downloadable Files*,” along with several figures that are “linked” to their respective spreadsheets. One particular figure file, Figure CD11.17, is an animated walk through of a part of a plant. The files can be accessed through the CRC Web site, at <http://www.crcpress.com/product/isbn/9781420061918>

Contents—Downloadable Files

PART I *Foundation*

Chapter 1	Water Treatment.....	3
TABLE CD1.2	Treatment Technology Matrix (Excerpt from Table CD1.2b).....	7
Chapter 4	Unit Process Principles.....	57
TABLE CD4.2(a)	Comparison between Finite Difference and Mathematical Solutions for Continuous Input of Salt Starting at $t = 0$	69
TABLE CD4.2(b)	Solution Finite Difference Mass Balance Equation—Continuous Input ($0.1 \leq t/\theta \leq 0.5$) of Salt	69
TABLE CD4.3	Solution Finite Difference Equation—Pulse Input ($0.1 \leq t/\theta \leq 0.5$) of Salt	70

PART II *Particulate Separations*

Chapter 5	Screening	79
TABLE CD5.2	Bar Screen Design Based on Hydraulic Criteria.....	81
TABLE CD5.7	Microscreen Coefficient and Subsequent Use of Coefficient for Design (Data from Envirex, 1985)—Excerpt Showing 24 Out of 40 Columns and 5 Out of 39 Rows.....	88
Chapter 6	Sedimentation	95
TABLE CDEx6.1	Determination of Maximum Particle Size for Stokes' Law to be Applicable	97
TABLE CD6.5	Materials Balance Calculations for Area of a Final Settling Basin	112
Chapter 7	Grit Chambers	135
TABLE CD7.1	Solution for Example 7.1—Shield's Equation for Scour in Grit Chamber	137
TABLE CD7.2	Spreadsheet Showing Calculation of Proportional Weir Sizing and Flow	138
TABLE CD7.3	Free Flow Ranges, Coefficients, and Exponents for Parshall Flumes of Various Throat Widths	140
TABLE CD7.4	Hydraulic Profile Calculation	141
TABLE CD7.5	Dimensions and Capacities for Parshall Flumes	143
TABLE CD7.6	Design of Rectangular Grit Chamber with Parshall Flume as Control	145
TABLE CD7.7	Calculated Parabolic Grit Chamber Section for Selected Parshall Flume	147
FIGURE CD7.11	Calculation of parabolic section.	147
TABLE CD7.14	Airflow and Power Calculations for Aerated Grit Chamber.....	157
Chapter 8	Flotation.....	163
TABLE CD8.2	Particle Rise Velocities as Function of Number of Bubbles Attached, B	173
TABLE CD8.3	Calculation of Required Saturator Pressure to Float Solids for Stated Conditions by Mass Balance	175

PART III *Microscopic Particles*

Chapter 9	Coagulation.....	191
TABLE CD9.6	Distribution of Aluminum Ion Hydrolysis Species with Varying pH.....	208
TABLE CD9.7	Determining the Distribution of Ferric Iron Hydrolysis Species with Varying pH	209

Chapter 10	Mixing	239
TABLE CD10.4	Calculations of n , P , P/V , P/Q , and G based on R and P	259
TABLE CD10.7	Complete-Mix Reactor Calculations of Residual Concentrations and Mass Remaining	264
FIGURE CD10.18	Residual concentration fraction as a function of t/θ	265
TABLE CD10.12	Calculations of Jet Flow, Jet Velocity, Pipe Velocity, Power Dissipated, G Values, $G\theta$ Values, Trajectory from Jet, etc.	274
FIGURE CD10.23	Trajectories of two jets	275
TABLE CD10.14	Example of Headloss, P , G Calculations for Static Mixer	279
Chapter 11	Flocculation	291
TABLE CD11.2	Calculation of Floc Specific Gravity by Equation 11.9	300
TABLE CD11.7	Floc Basin Paddle-Wheel Data for Different Motor Controller Settings and Associated Calculations of Torque, Power Expended, G , P , and R for First Compartment of a 76 L/min (20 gpm) Pilot Plant	314
TABLE CD11.8	Calculation of Camp's Slip Coefficient, k , Using Data from Pilot Plant	316
FIGURE CD11.17	Flocculation and sedimentation finished designs (animated walk through of Fort Collins Water Treatment Plant, 2000 Addition. (a) Animation 1 Flocculation Basin – Plate Settlers Walk-Through upstairs—PAK1B AVI (excerpt shows flocculation basins). (b) Animation II Flocculation Basin – Plate Settlers Walk through downstairs—PAK1A AVI (excerpt shows corridor between basins; paddle-wheel motors are visible on the walls).	317
Chapter 12	Rapid Filtration.....	329
TABLE CD12.3	Excerpt—Calculation of Transport Coefficients and Filter Coefficients by Excel Spreadsheet	348
TABLE CD12.7	Excerpt—Bed Expansion as Function of Backwash Superficial Velocity and Calculation of Minimum Fluidization Velocity with Correction	366
Chapter 13	Slow Sand Filtration.....	395
TABLE CD13.2/CDE.2	Conversion between K and k Including Headloss Calculation from k	402
Chapter 14	Cake Filtration	423
TABLE CD14.2	Pressure Loss as a Function of Hydraulic Variables as Calculated by Equation 14.8.....	435
TABLE CD14.*	Headloss Calculations as Function of Hydraulic Variables (Calculated by Equation 14-*).	435
FIGURE CD14.10	Headloss versus time plots for five grades of diatomite as calculated by Table CD14.2.....	437
TABLE CD14.5	Description of 12 DE Plants and Operating Protocols	443
 PART IV <i>Molecules and Ions</i>		
Chapter 15	Adsorption.....	457
TABLE CDEx15.1	Determination of Headloss in GAC Column Given k	463
TABLE CD15.8	Design Protocol for GAC Packed-Bed Reactor.....	490
TABLE CD15.A.1	Freundlich Isotherm Coefficients for 141 Synthetic Organic Compounds—Adsorbent was Filtrasorb ^{300®}	500
Chapter 16	Ion-Exchange.....	511
TABLE CD16.A.1	Conversions of Density of Particles	530
TABLE CD16.A.2	Conversions of Ion-Exchange Capacity	531
Chapter 17	Membrane Processes	539
TABLE CD17.6	Calculation of Osmotic Pressure by van't Hoff Law of Dilute Solutions.....	555

Chapter 19	Disinfection	607
TABLE CD19.4	Calculation of Ct 's for <i>Giardia</i> Cysts for Different C , pH, T Conditions (Excerpt)	616
TABLE CD19.6	Concentrations of $[Cl_2]$, $[HOCl]$, and $[OCl^-]$ as a Function of pH for a Given $[Cl_2]$ Concentration	619
FIGURE CD19.5	Calculations based on 4 mg/L ($5.7 \cdot 10^{-5}$ molar) solution of Cl_2 added to solution (from mass balance, charge balance, equilibrium relations) as function of pH. (a) Concentrations of chlorine species. (b) Fraction, α , of different chlorine species	620
Chapter 21	Precipitation	661
FIGURE CD21.1	pC versus pH diagram for Ca^{2+}	666
TABLE CD21.2	Concentrations of $[Ca^{2+}]$ as a Function of pH	666

PART V *Biological Treatment*

Chapter 23	Biological Reactors	721
TABLE CD23.4	Excerpt from Excel Spreadsheet for Dynamic Activated-Sludge Model	734
FIGURE CD23.6	Flow and BOD over 24 h and calculated effluent BOD, Fort Collins WWTP, 1990. (a) Influent flow. (b) Influent BOD and calculated effluent BOD.	734
TABLE CD23.6	Excerpt from Biofilm Trickling-Filter Model Spreadsheet	740
FIGURE CD23.8	Trickling-filter model output	741
Pre Appendix Tables		757
TABLE CDQR.1	Constants—Quick Reference	757
TABLE CDQR.2	Units and Conversions—Quick Reference	758
TABLE CDQR.3	SI Prefixes—Quick Reference	761
TABLE CDQR.4	Coefficients for Calculation of Variables—Polynomial Best Fit Equations	762
TABLE CDQR.5	Coefficients for Calculation of Variables—Exponential Best Fit Equations	763
TABLE CDQR.6	Miscellaneous Notes	764
Appendix D	Fluid Mechanics—Reviews of Selected Topics	791
TABLE CDD.2(a)	Spreadsheet Calculating Pressure Surface for Under-Drain System (Excerpt)	800
TABLE CDD.2(b)	Abstract of Head Levels and Flows in Header Pipes and Laterals for a Filter Bed	800
FIGURE CDD.7	Pneumatic grade line with delineation of changes for flow to submerged diffuser (figure is also embedded in Table CDD.3)	801
TABLE CDD.3	Pneumatic Analysis of Air Flow to Aerated Grit Chamber (by Bernoulli Relation) to Obtain Pressure Inputs to Compressor	805
TABLE CDD.5	Air Flow Calculation for Compressor for an Aerated Grit Chamber (Example)	809
TABLE CDD.6	Combined Pipe Flow and Compression Spreadsheet	810
Appendix E	Porous Media Hydraulics	819
TABLE CDE.2	Conversion between K and k Including Headloss Calculation from k	823
TABLE CDE.4	Hydraulic Gradient Calculated by Forchheimer Equation	830
Appendix F	Alum Data and Conversions	833
TABLE CDF.3	Alum Conversions	842
TABLE CDF.3	Alum Conversions (Excerpt Showing only Tables CDF.3(a) and (b))	842
Appendix G	Dimensionless Numbers	847
TABLE CDG.3	Matrix of Physical Phenomena and Associated Dimensionless Numbers	850

Part I

Foundation

Taking time to assimilate themes common to all unit processes helps to put order and understanding into learning about water treatment as opposed to a collection of facts and equations. Therefore, Part I describes some of the foundations, or “building blocks,” of the field. This *foundation* constitutes the first four chapters.

Unit processes: Chapter 1 describes how water treatment as a topic can be disaggregated to unit processes, principles, and technologies. Examples of treatment trains illustrate a variety of treatment applications. These expand beyond the traditional municipal potable water and wastewater to include tertiary treatment, modified water treatment, industrial process water, and industrial wastewaters. The variety of applications is almost without limit.

Contaminants: Chapter 2 looks at the variety of contaminants found in water. Selected ones must be removed in order to provide for further uses of water either as required by law or as motivated by a private need such as for industrial process water.

Models: In Chapter 3, the idea of a “model” is described in terms of its variety of forms. Models are at the root level of design. We use models in everyday life ranging from mental images to photographs. The designer uses whatever may be available, for example, inspections of existing plants, judgment, rules of thumb, equations, mathematical models, physical models, computer animations, etc. All of these are models and are means to project from the abstract to operation and design.

Reactors: The idea of the “reactor,” in Chapter 4, applies to many unit processes. It is the notion that if we pass a dissolved or particulate contaminant through a particular kind of “black-box,” changes will occur. The reactor concept is the basis for formulating these changes mathematically. The general idea applies to a variety of unit processes, for example, settling, mixing, deep bed filtration, adsorption in packed columns, ion-exchange, membranes, gas transfer, disinfection, precipitation, oxidation, activated sludge, bioreactors, etc. The concept applies to natural systems where “passive” changes occur, as well as to engineered systems.

1 Water Treatment

The topics covered in this chapter include a review of unit processes, the genesis of water treatment as a technology, a discussion of units, and an overview of how the book is organized.

1.1 WATER TREATMENT IN-A-NUTSHELL

Any water treatment is done in the context of a treatment train, a collection of unit processes. Such unit processes may include screening, sedimentation, flotation, coagulation, filtration, adsorption, ion exchange, gas transfer, oxidation, biological reactions, and disinfection. The aggregation selected, i.e., the treatment train, if applied to full scale with all of the needed appurtenances and engineering to make it function on a continuous basis, is a water treatment plant (WTP). The objective of water treatment, by this treatment train, is to effect a required change in water quality.

The water being treated may be any water, e.g., ambient water used as a source for drinking water, municipal or industrial wastewater, contaminated groundwater, brackish water, seawater, or the product water from any treatment plant. The treatment train employed in a WTP depends, first, upon the source water and the objectives for the effluent water and, second, on other factors, such as capital and operating costs, reliability, ease of operation, traditions, current practices, etc. The relative importance of these other factors depends on the project at hand.

1.1.1 WATER TREATMENT PLANTS

To bring into existence an operating WTP requires more than a consideration of unit processes. A well-conceived treatment train and the proper design of its unit processes is the heart of any design. But much more is required to support the process design. All plants must have, e.g., stated not in a particular order, various kinds of sampling, metering and monitoring, control of flows with pumps and valves of various types, facilities for receiving and storing chemicals along with their subsequent metering and injection, safety measures regarding chemicals and many other aspects of plant operation, laboratory support, utility tunnels, structural design of various tanks, hydraulic design for various purposes including setting the hydraulic grade line of a plant, etc. In a plant with granular activated carbon (GAC), transport of the treated carbon to and from the reactors must be provided along with provision for regeneration either on-site or off-site. In addition, the storage tanks, usually steel, must be protected from corrosion. The distinction between the design of water treatment processes and a WTP is between principle and implementation.

The process principles must be adhered to but they must be provided the means for being implemented, i.e., in terms of a plant. The latter is not excluded in this book, but is not the main focus. The two areas are complementary. Process design can be taught in school. But in putting it all together, experience is most important.

1.1.2 RESIDUALS

As an axiom of water treatment, residuals are always a by-product. They are unwanted, but must be dealt with. For example, in membrane treatment, the “concentrate” water flow is often limiting with respect to the feasibility of an installation. The residuals stream in water treatment includes the sludge from settling basins and the backwash water of filtration. Settling ponds must be provided to decant the water and to dispose of the resulting sludge. In wastewater treatment, a variety of treatment trains may be employed to process the solid streams, with some kind of recycle or disposal being the end result.

Some of these required tasks can be taught and other aspects must be learned by experience. Some introduction is helpful, but experience and visits to installations is essential. Many questions can be answered readily and the problems may be put into perspective by visits to plants complemented by discussions with operators and experienced engineers.

1.2 ORGANIZATION OF WATER TREATMENT KNOWLEDGE

Common themes in organizing water knowledge include

1. Treatment for a particular purpose, such as for drinking water, wastewater, industrial wastewater, and contaminated groundwater
2. Treatment of particular contaminants
3. Unit processes

From about 1880 to 1960, knowledge developed along the lines of the first approach, i.e., drinking water treatment, wastewater treatment, and industrial wastes treatment. Then treatment of hazardous wastes emerged about 1980, employing some of the same unit processes. Desalting of brackish waters and seawater became issues beginning about 1960. Thus, we have had books and persons who think along the lines of drinking water treatment and others who think of municipal wastewater treatment, with commensurate books and journals, and yet another group who specializes in treatment of industrial wastes, etc.

BOX 1.1 CONTEXT AND FIT

A particular type of situation is the *context* for a design and has to do with water quality, treatment objectives, operation capabilities, financing, etc. The *form* is the unit process/technology adopted. The *fit* is the relationship between the *context* and the *form*. An *appropriate* fit is desired. In other words, the process/technology selected must be appropriate for the context. These ideas are central to design.

As an example, a slow sand filter may be appropriate technology for a small community, since materials are available locally, operation is “passive,” i.e., not requiring operator skill, and parts are simple and easily repaired locally. On the other hand, slow sand may not be appropriate for a large community as the labor requirement is much more than for a rapid rate plant. For the latter, automation is feasible and parts and skilled labor are likely to be readily available.

In some cases, the paradigm for thinking has been along the lines of treatment for specific contaminants, mostly those that are regulated, or perhaps those that pose an industry problem. For example, halogenated hydrocarbons have been regulated in drinking water in 1978 starting with tri-halo-methanes. Nutrients in wastewater have been a treatment focus since the early 1970s as a means to reduce algae blooms in ambient waters. Heavy metals, an industrial waste problem, have also been regulated since the 1970s. There are books as well as articles dedicated to these topics.

In the 1960s, some in the academic community began to adopt the unit operations/unit processes approach in organizing the knowledge of water treatment. This approach was inspired by two books, *Unit Operations of Sanitary Engineering* (Rich, 1961) and *Unit Processes of Sanitary Engineering* (Rich, 1963), and reinforced by persons pursuing graduate degrees who had taken courses in chemical engineering.

In comparing the three approaches, the first is limited in perspective to the problem area at hand (e.g., drinking water treatment, municipal wastewater treatment, industrial wastewater treatment, and hazardous wastes treatment). Screening, e.g., as a bar screen in wastewater treatment is viewed as a means to protect pumps from items that might cause clogging. In water treatment, screening may be a microscreen to remove algae. As a unit process, screening is a means to retain objects and particles for whatever purpose. The difference is in the viewpoint. The first two are by nature empirical and specific, while the third is adaptable to the purpose without the constraints of tradition. With the first two approaches, one lacks the broad perspective that screening may be applied to any problem area.

In this book, we use the unit processes approach. The unit process approach includes operative principles, traditions, practices, empirical methods, technology forms, and the spectrum of applications.

1.3 UNIT PROCESSES

This book presents the topic of water treatment in terms of unit processes, which are discussed in the following chapters. For each unit process considered, principles and practices are explained. The unit processes approach is common to the field of chemical engineering and has been assimilated by the field of environmental engineering.

1.3.1 DEFINITIONS

A water treatment unit process is defined as an engineered system to effect certain intended state changes for the water. Examples include screening, gravity settling, coagulation, flocculation, filtration, gas transfer, ion exchange, adsorption, membrane separations, biological treatment, disinfection, oxidation, and chemical precipitation (Sanks, 1978; Letterman, 1999). These unit processes are the topics of this book. Some of the definitions are as follows:

- *Screening*. The retention of a substance by a screen that has a mesh size smaller than the substance to be retained.
- *Gravity settling*. A particle falling under the influence of gravity is called sedimentation.
- *Coagulation*. The charge neutralization of a negatively charged colloid, usually by chemical means, such as the use of alum or a ferric compound.
- *Flocculation*. A unit process that promotes collisions between particles that attach to each other upon contact, growing in size to increase settling velocity.
- *Filtration*. The convection of a water stream through a porous media with the intent to retain suspended particles within the media.
- *Gas transfer*. The transport of gas between the dissolved phase in water and a gas phase.
- *Ion exchange*. The exchange of benign ions (such as Na^+) bonded to sites within an ion-exchange material (such as a zeolite mineral or a synthetic resin) intended to be displaced by an ion targeted for removal (such as Ca^{2+}) that has a stronger bonding force.
- *Adsorption*. The attachment of a molecule to an adsorption site provided by an internal surface of an adsorbent material. Activated carbon is the best-known adsorbent for an engineered system, although virtually any solid material can provide adsorption sites.
- *Membrane separation*. The four types of membrane processes are as follows:
 1. Microfiltration (removes colloids and bacteria)
 2. Ultrafiltration (removes viruses)
 3. Nano-filtration (removes large molecular weight organic molecules and some ions)
 4. Hyper-filtration, more commonly called “reverse osmosis” (removes molecules and ions)

The membrane processes are different in pore size and in pressures required; defined pores may be lacking, in fact, for the latter two membrane processes:

- *Biological treatment.* A reaction between an organic molecule and a microorganism
- *Disinfection.* The inactivation of microorganisms
- *Oxidation.* The gain of electrons by chemical reaction
- *Precipitation.* The formation of a solid substance from ions in solution

To the extent possible, these unit processes are described in terms of principles. As a rule, however, scientific principles alone do not provide for a “complete” engineering solution.

Engineering has the characteristic that a solution to a problem is the important thing. A problem to be solved cannot wait for a rational explanation. So while the scientific explanation is sought, it is often necessary to make do with some means to make a decision about design. Such methods may involve judgment, a knowledge of scientific principles, modeling, laboratory testing, lore concerning how things have been done in the past, rules of thumb, the use of some kind of calculation method such as a loading rate, associated criteria, etc. Thus, while the book describes what is known as the rationale for a process design, methods used in practice are reviewed also. (The view taken here is that the foregoing provides a means for decision-making. Scientific certainty and accuracy are sought, but the main thing is to provide a basis for achieving a defined level of system performance and doing so economically and with a social “fit.”)

A “state” is defined here as the water quality characteristics of a given parcel of water and may include concentrations of suspended solids (including organisms), ions, and molecules; temperature; pH; etc. A treatment “process” is intended to cause a desired change of the state of a volume of water. The idea of a water quality “state” was taken from the field of physical chemistry in which the state of a gas is defined by its temperature, pressure, and volume.

1.3.2 TECHNOLOGIES

For a given unit process, a technology is a means for implementation. For example, a rapid filter is a means to implement a “deep-bed” filtration process. The rapid filter includes the array of appurtenances to make it work, e.g., the filter box depth and area, under-drain system, and backwash system. Rules of thumb, tradition, and manufacturer’s standards govern the sizing and characteristics of each component.

In short, a technology is a “package” of design guidelines and components that result in a system that supports a workable process. The manufacturer may provide a complete package or some of all of the supporting components.

1.3.3 BREADTH OF UNIT PROCESSES AND TECHNOLOGIES

To illustrate the idea further, Table 1.1 lists some 15 unit processes with samples of associated treatment technologies. The list of associated technologies is not complete, nor does it show the range of variation. The technologies are listed generically. If proprietary technologies were listed, Table 1.1 might be several pages long. All of this is mentioned so that one may gain an appreciation for the breadth of the number of technologies that have been developed.

Table CD1.2 is an excerpt from a matrix with some 700 contaminants listed in rows and 11 basic unit processes listed in columns with selected technologies under each unit process (Champlin and Hendricks, 1993). Columns further to the right list variations. Looking down the columns, the contaminants that may be subject to treatment by a given technology are designated by a code in the intersecting cell based upon the expected percent removal. The matrix expands on what is shown in Table 1.1 but includes a listing of contaminants. Table CD1.2a shows an overall layout of the matrix, i.e., how to navigate, while Table CD1.2b is the large matrix with some 700 rows and 100 columns. The idea of the large matrix is to give an appreciation for the scope of water treatment as a field of practice.

1.3.4 PROPRIETARY TECHNOLOGIES

Proprietary innovation plays a large part in technologies. Several manufacturers offer their own “packages” of technology for the deep-bed filtration process, for example. To illustrate, the Parkson Dynasand® filter is a moving bed filter that takes off the floc-saturated media at the bottom, replenishes the filter bed at the top, and so backwash is not required. The Culligan Multi-Tech® filter is a complete package plant that provides the means for flocculation within a coarse media preceding the main filter and is designed for the complete automation of the filtration process. The Infilco-Dregemont ABW® (automatic backwash) filtration system is a shallow-bed filter comprised of a series of transverse cells 305 mm (1.0 ft) wide. A traveling bridge with a hood to collect the backwash flow and a backwash pump with “shoe” that places the backwash plumbing over the under-drain opening in the finished water channel provides for a short duration backwash of a single cell. The bridge moves then to the next cell and the filter as a whole is never taken out of operation.

The filtration example illustrates the role of proprietary companies in making successful a given process. Essentially, an array of proprietary technologies have been developed for each unit process either to provide support for a generic design such as ancillary equipment or to provide a full operational package technology. Two or three of the unit processes have been developed largely under the impetus of proprietary research. An example is the membrane processes that have evolved commercially since the 1960s and have reached the status of widespread use.

TABLE 1.1
Unit Processes and Associated Technologies

No.	Unit Process	Principle	Treatment Technologies
1	Screening	Retention of objects or particles larger than screen openings	Trash rack Bar screen Fine screen Comminutor Microscreen
2	Chemical precipitation	Solubility product of reaction “product” is very low, e.g., 10^{-10} – 10^{-30} ; precipitate settles	Lime softening Metals removal
3	Coagulation	Negatively charged colloids are charged neutralized by cation cloud	Rapid mix In-line mixer Static mixer Submerged jet
4	Flocculation	Micro-flocs contact with each other to form settleable flocs. Contacts are induced by controlled turbulence or advection through a sludge blanket	Paddle-wheel flocculator Porous media Solids contact flocculation Turbine flocculator
5	Settling	Gravity force causes fall of particles heavier than water and rise of particles lighter than water	Horizontal flow Up-flow Tube Plate American Petroleum Institute (API) oil separator
6	Flotation	Gas bubbles attach to particles to create buoyant force causing rise	Dissolved air Diffused air
7	Filtration-deep bed	Charge neutralized micro-flocs are advected to “collectors” (usually sand and anthracite) where they “attach” (by van der Waal’s forces)	Conventional 760 mm (30 in.) dual media Mixed media Mono media, 1–3 m (3–10 ft) deep Slow sand Proprietary variations
8	Cake filtration	Particles are retained by smaller pores as media is added concurrently (so that the media hydraulic conductivity does not change)	Diatomaceous earth Shapes of septum Plate and frame Candle
9	Membrane filtration	Particles, e.g., ions, organic molecules, viruses, bacteria, cysts, mineral matter, etc., that are larger than the membrane pore size are retained while water and matter smaller than the pore are transported, by advection, under a pressure gradient	Microfiltration Ultrafiltration Nano-filtration Hyper-filtration Shapes of membrane Spiral-wound sheets Hollow fiber Electrodialysis
10	Adsorption	Molecules and particles will adsorb on an “adsorbent,” a material that provides “sites” for attachment by van der Waal’s forces Ion-exchange is the same except ions attach to sites and force is electrostatic	Granular activated carbon Powdered activated carbon Activated alumina Ion-exchange Zeolite Resin
11	Gas transfer	Concentration gradient for dissolved gas is induced to cause mass transfer Rate of mass transfer is proportional to gradient	Turbine aeration Diffused air Packed towers Steam stripping

TABLE 1.1 (continued)
Unit Processes and Associated Technologies

No.	Unit Process	Principle	Treatment Technologies
12	Oxidation	Electrons are removed from outer shell of substance being oxidized	Chlorine Chlorine dioxide Ozone Ozone-hydrogen peroxide Potassium permanganate Ultraviolet radiation
13	Supercritical oxidation	Pressure and temperature are raised to create supercritical conditions	Wet air oxidation High pressure high temperature oxidation
14	Aerobic biological treatment	Bacterial enzymes permit metabolism of organic molecules with products new bacteria, carbon dioxide, and water	Activated sludge Complete mix Plug flow Aerated lagoon Facultative pond Fixed film reactor Trickling filters (traditional) Bio-filters (forced air) Rotating biological contactor
15	Anaerobic biological treatment	Two stage reaction: acid formers metabolize organic molecules with organic acids as products and methane formers metabolized organic acids to produce methane and carbon dioxide	Anaerobic biological reactor Digester Anaerobic pond Anaerobic filter

TABLE CD1.2
Treatment Technology Matrix (Excerpt from Table CD1.2b)

No.	Water Contaminant	CAS Numbers	Contaminant Type	Empirical Formula
1	Acenaphthene	83-32-9	PAH	C ₁₂ H ₁₀
2	Acenaphthylene	208-96-8	PAH	C ₁₂ H ₈
3	Acetaldehyde	75-07-0	Aldehyde	C ₂ H ₄ O
4	Acetamide	60-35-5	Not found	
5	Acetamide, N[4-[(2-hydroxy-5-methyl...)]]	2832-40-8	Not found	
6	Acetone	67-64-1	Ketone	C ₃ H ₆ O
7	Acetone cyanohydrin	75-86-5	Nitrile	C ₄ H ₇ NO

1.3.5 STATUS OF UNIT PROCESSES

The treatment of water became an issue in the first decades of the nineteenth century with drinking water. In this context, James Simpson developed the slow sand filtration technology for London, enumerating design guidelines and support components to have a workable process. Slow sand became an accepted technology for drinking water by the 1870s and was in widespread use, particularly in Europe, by 1890, where it was credited with saving Altona, Germany, from a cholera epidemic. The

treatment of wastewaters became an issue after 1860 in England where chemical precipitation became one of the first unit processes, but did not develop into widespread use. In 1880, the Lawrence Experiment Station was established (Massachusetts, 1953) that later led in the development of several technologies, including trickling filters, and where experimentation inspired Arden and Lockett to develop activated sludge in England in 1914. Settling, called “subsidence,” was well established by 1900; the technology was cheap and was an obvious alternative. By 1885, deep-bed filtration was an innovation that by 1900 had become established in America. In Europe, Klaus Imhoff developed the Imhoff Tank about 1905 and Cameron in England developed the septic tank. How the stage was set for the development of environmental engineering as a field from Ancient times to 1900 was reviewed by Symons (2001).

Ion exchange had been known scientifically by early 1800, and became an established technology for softening by 1924 using zeolites. The use of chlorine, ozone, and ultraviolet radiation as disinfectants were established by 1900. Ozone was adopted widely in Europe, while chlorine became established in America. By the third decade of the twentieth century, gaseous chlorine became the technology of choice (in the United States). Advances in the application of technologies have continued over the following decades. The point is that water treatment technologies have been developing and expanding starting only since 1829 with slow sand. The impetus has been societal issues that were recognized as government responsibilities with advances through research and practice.

1.3.6 FUTURE OF TREATMENT

There is little doubt that technologies will continue to evolve, particularly if the market exists for improved applications of unit processes. Looking at the unit processes, some 15 are listed in Table 1.1; they were identified based upon fundamental principles. Of the 15 identified, and looking at the underlying principles of each, the question would be as follows: Could principles not yet used be applied for separating contaminants from water? While any predictions are uncertain by nature, we could say with safety that any new ones would have to be based on remaining principles that may cause a change of state of a substance.

1.3.7 ENERGY EXPENDITURE FOR TREATMENT

A fundamental axiom of any treatment process is that a separation is involved. The separations involve removing particles from water, ions from water, and molecules from water. In each case the principle is that the entropy of the particles, ions, or molecules must be reduced. By the second law of thermodynamics this can occur only by an input of energy. Any treatment process cannot violate the principle of the second law. In other words, energy must be expended to effect any

kind of separation. Then to make any process feasible from an engineering point of view, there must be a compromise between energy cost and the speed of the process (the more irreversible the process, the higher is its velocity, but the higher the energy cost). The second law places an inherent limit on what may be expected.

1.4 TREATMENT TRAINS

The configurations of unit processes that may comprise treatment trains are perhaps as numerous as there are combinations of the unit processes listed in Table 1.1. Those that are most common are (1) for potable water and (2) for wastewater. Figure 1.1 shows schematic sketches of treatment trains for potable water, Figure 1.1a, and for municipal wastewater treatment, Figure 1.1b, respectively. To illustrate the latter, Figure 1.2 shows an aerial photograph of the wastewater treatment plant (WWTP) for the City of Colorado Springs, c. 1972.

The unit processes shown for Figure 1.1a and b are common, but considerable variation is possible. For example, in potable water treatment, Figure 1.1a, plain sedimentation may be omitted if the source is a lake. A variation in the filtration process, called “in-line” filtration, omits flocculation and

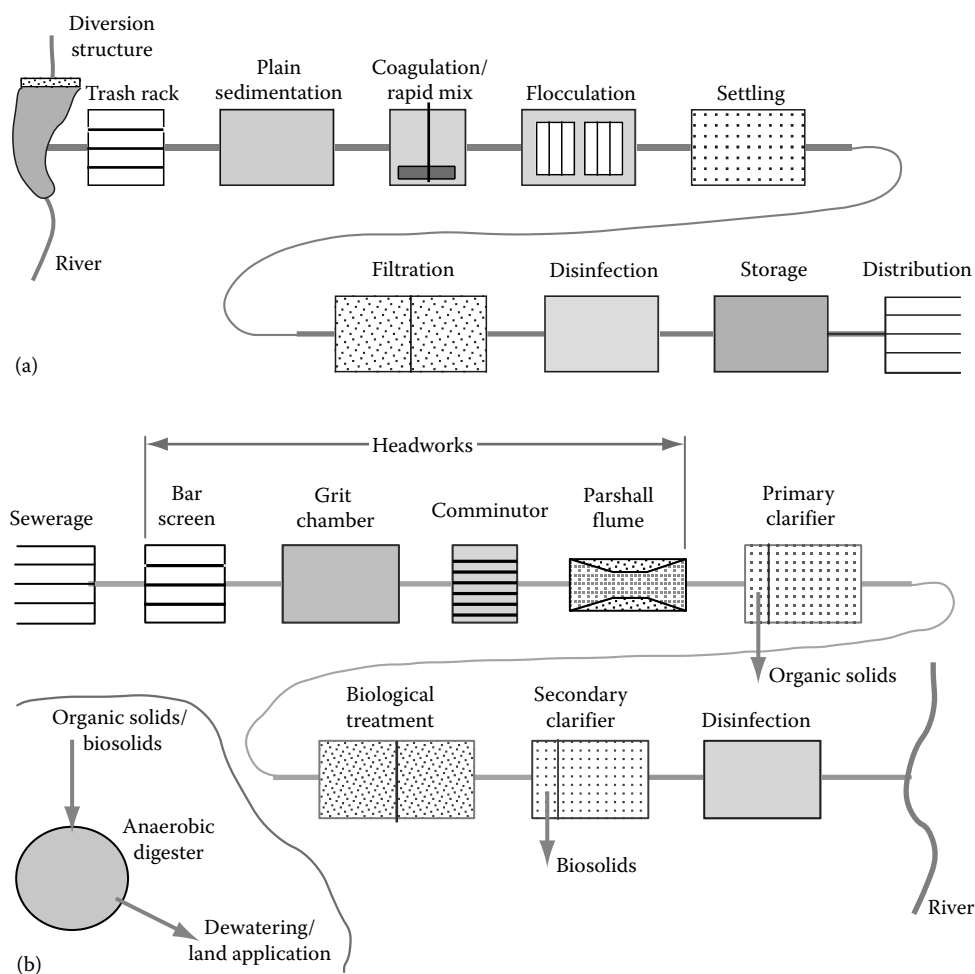


FIGURE 1.1 Treatment trains—schematic drawings: (a) potable water and (b) municipal wastewater.



FIGURE 1.2 Aerial photograph of WWTP, City of Colorado Springs, c. 1972. (Photo courtesy of City of Colorado Springs, Colorado Springs, CO.)

settling. For disinfection, chlorine has been traditional in the United States, while ozone is common in Europe. In municipal wastewater treatment, as in Figure 1.1b, finer bar screens have been used in lieu of comminutors; also, tertiary treatment could be added.

The selection of unit processes depends upon the contaminants present in the source water and the objectives to be achieved by treatment. The selection of technologies depends on contextual factors; costs; preferences of the client; and the engineer's vision, experience, and knowledge. Considerable variation is possible within each treatment train in the selection of specific technologies.

1.4.1 TERTIARY TREATMENT

In municipal wastewater treatment, additional unit processes may include any or all of the following: filtration to reduce particles, precipitation by lime to reduce phosphates, and adsorption with activated carbon to reduce organic molecules. If the goal is to produce potable water, then hyper-filtration (reverse osmosis) may be added along with several other unit processes.

1.4.1.1 Cases

Usually tertiary treatment situations have involved small flows, e.g., $0.044 \text{ m}^3/\text{s}$ (1.0 mgd). In some cases, such as in providing water for irrigation, sand filtration without coagulants has been used. The Parkson Dynasand moving bed filter has been used in a number of such instances as has the ABW traveling bridge filter of Infilco-Degremont. These are “package”-type technologies that can be added to any conventional treatment train. These cases illustrate the systems context of most water treatment projects and the role of political factors. Both are inherent in any public project.

1.4.1.1.1 Aspen

The City of Aspen, Colorado, installed an ABW traveling bridge filter, developed for water treatment, to treat effluent from its conventional wastewater treatment train. The effluent discharge permit for discharge to the Roaring Fork River required a “20/20” standard (20 mg/L suspended solids/20 mg/L bio-

chemical oxygen demand). The river has high value as a fishery and for recreational use, and the filters provide a margin of safety.

1.4.1.1.2 Ignacio

Figure 1.3a is a photograph of an ABW system as used for drinking water treatment at Ignacio, Colorado. Figure 1.3b is a cutaway perspective of the ABW system. The basic system is the same for water or wastewater, albeit the media may be different from one use to another. The traditional media is sand with a depth of 305 mm (12 in.). A “cell” is 203 mm (8 in.) wide and its length is across the bed of the filter.

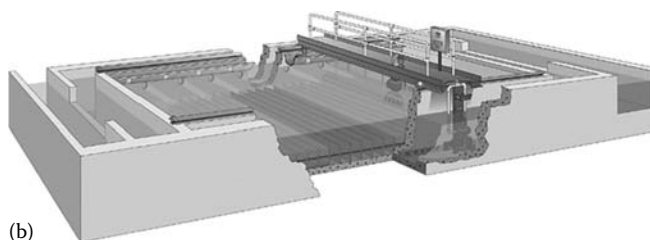


FIGURE 1.3 ABW (automatic backwash) filtration system. (a) ABW filter installation used for small community. (b) Perspective drawing of ABW filter. (Photo courtesy of Infilco Degremont, Richmond, VA.)

The traveling bridge backwashes each cell individually and moves continuously from one end of the filter bed to the other and back again. The flow through each cell declines as the media clogs and is restored to the clean-bed level after backwash.

1.4.1.1.3 Colorado Springs

Because of a drought during the period 1955–1959, the City of Colorado Springs (Colorado Springs, c. 1972) has had tertiary treatment following traditional treatment since 1960. This initial treatment was filtration only and the water was used for golf course and park irrigation, and was later called the “irrigation circuit”; the treatment capacity was $Q = 0.394 \text{ m}^3/\text{s}$ (9.0 mgd). In 1970, a second treatment train was added and was called an “industrial circuit,” with capacity $0.0876 \text{ m}^3/\text{s}$ (2.0 mgd). The effluent was used for cooling tower water at a municipal power plant with the cost of treatment about $\$0.07/\text{m}^3$ or $\$260/\text{mg}$.

1.4.1.1.3.1 Irrigation Circuit The irrigation circuit had four 3.658 m (12 ft) diameter dual media pressure filters with filtration velocity 36.7 m/h (15 gpm/ft^2). The media was 0.91 m (3 ft) of 1.5 mm sand on the bottom with 1.52 m (5 ft) of 2.8 mm anthracite on top.

1.4.1.1.3.2 Industrial Circuit The treatment train for the industrial circuit was coagulation and settling by means of a “solids-contact” clarifier, re-carbonation with carbon dioxide, filtration with anthracite and sand, and carbon adsorption. The solids-contact unit, 14.63 m (48 ft) diameter, used a lime dose of $300\text{--}350 \text{ mg/L}$ of CaO , which raised the pH to 11.5. Following the solids contact unit, the pH was lowered to 7.0 by carbon dioxide (from furnace gas used for carbon regeneration) supplemented by sulfuric acid. Filtration using coarse media was the next step in order to provide redundancy in solids removal in the event of upset of the solids-contact clarifier. Carbon adsorption by GAC was the next step, which used two columns in series (Figure 1.4). Each column was 6.096 m (20 ft) diameter and 4.267 m (14 ft) high, packed with 3.048 m (10 ft) of 8×30 mesh GAC with mass 41,864 kg (94,000 lb). For the design flow of $0.0876 \text{ m}^3/\text{s}$ (2.0 mgd), the hydraulic loading rate was 10.39 m/h (4.25 gpm/ft^2). Removal of COD was $0.50\text{--}0.60 \text{ kg COD/kg carbon}$ ($0.50\text{--}0.60 \text{ lb COD/lb carbon}$). The carbon columns were backwashed daily.

1.4.1.1.4 Denver Reuse Demonstration Plant

The Denver Reuse Demonstration Plant, $Q = 0.044 \text{ m}^3/\text{s}$ (1.0 mgd), was in operation in the period 1985–1991. The source water was effluent from the nearby Denver Metro WWTP (called Denver Metro Water Reclamation Plant). The “reuse plant” treated water that exceeded standards for potable water.

The plant cost was \$20 million with about \$10 million for studies to determine health risks. The treatment train included



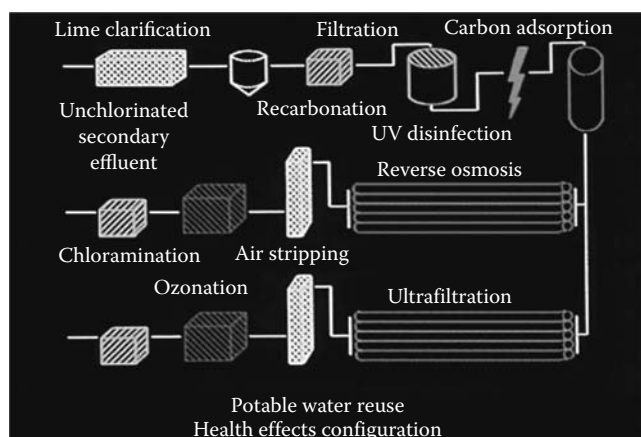
FIGURE 1.4 GAC columns for tertiary treatment at Colorado Springs, c. 1972.

lime precipitation, filtration, ion exchange, adsorption with activated carbon, ozone oxidation/disinfection, hyper-filtration, and chlorination. Side streams investigated different disinfectants, various membranes such as micro-filtration and ultrafiltration, and ozonation prior to adsorption. Figure 1.5 shows the overall plant schematic (for the “health-effects” treatment train) and three photographs that illustrate the substantial size of the plant.

The plant was “demonstration” size, and was intended to demonstrate the feasibility of direct potable reuse. While the purpose of a pilot plant is to develop design guidelines for a full-scale plant, a demonstration plant is much larger in size and may have several purposes, both technical and political. The former relate to such issues as long-term health effects due to trace amounts of organics, the cost of operation, the manpower required, reliability, and the assessment of unforeseen issues (such as the durability of the lining of the carbon columns). This does not mean that process issues are ignored, but only that the emphasis shifts (as opposed to a pilot plant) to questions that require experience at a full-scale level of operation. The political aspects are equally important. The reuse plant had an attractive, architect-designed, exterior appearance with equally pleasing interior. A water fountain of its product water was located in the lobby, and the plant hosted innumerable tours and published many papers and had high visibility from local to international levels. The program to implement potable water reuse had included the issues of public acceptance, and confidence and need for political support.

1.4.2 INDUSTRIAL WASTEWATER TREATMENT

Regarding industrial wastewater treatment, the treatment technologies are usually the minimum required to meet the regulatory requirements in force. This may range from settling to



(a)



(b)



(c)



(d)

FIGURE 1.5 Denver Potable Reuse Demonstration Plant, c. 1989. (a) Flow schematic. (b) Lime settling and chemical silos. (c) Pressure filters. (d) Carbon columns. (Courtesy of Denver Water Department, Denver, CO.)

remove soil sediments and land treatment to remove organic molecules for sugar beets, to settling and anaerobic ponds for meat packing, to precipitation of heavy metals for the electronics industry and metals industry. Many industries, depending on policies and plant management, take pride in exceeding legal requirements.

1.4.2.1 Cases

Two cases are reviewed to indicate the variety of circumstances that influence the selection of unit processes that comprise treatment trains for industries. The circumstances of industries are highly variable, and so there is a wide variation in treatment processes.

1.4.2.1.1 Coors Brewery

The Miller-Coors Brewery, formerly Coors Brewery until merger in 2008, in Golden, Colorado, utilizes biological treatment, Figure 1.6, and had a 30/30 (BOD/TSS) effluent discharge permit for the adjacent Clear Creek that flows to the South



FIGURE 1.6 Wastewater treatment at Miller-Coors Brewery, Golden, Colorado. Pure-oxygen-activated sludge reactors are in background and underground. (Courtesy of Miller-Coors Brewery, Golden, CO.)

Platte River about 16 km (10 mi) downstream. The first plant was built in 1954, i.e., 18 years prior to being required by federal/state regulations. In 1981 a new plant, dedicated to the Coors Brewery industrial wastes (i.e., malting, brewing, and packaging) was put on line. (The 1954 plant then served only the City of Golden, along with sanitary wastes from other industrial operations and industrial wastes from the can manufacturing and ceramics facilities.) The new wastewater treatment system (i.e., the 1981 plant) included a coarse screen and grit removal (the latter to remove barley and other grain particles), an equalization basin to mitigate the effects of batch discharges, primary settling, activated sludge treatment using pure oxygen, and secondary settling. The plant was designed with the filtration of secondary settling effluent, using Parkson Dynasand filters with discharge to Clear Creek. In the years since 1981, the plant has been modified to more effectively and more economically achieve its objectives.

In 2001, an anaerobic pretreatment plant was built at site of the 1981 WWTP; the anaerobic plant receives about 60% of the organic loading from the brewery and removes about 65%–85% of the soluble organics, depending upon the hydraulic detention time. (The anaerobic process is sometimes used for high-strength industrial wastes as a means to reduce the loading to an aerobic biological treatment system. In the case of Coors, the BOD varies but about 1800 mg/L may be considered representative.) The Parkson Dynasand filters were taken out of operation in 1999 due to maintenance difficulties caused by adhesion of a cationic polymer to the filter media. The polymer was used in secondary settling, and in the evaluation of the trade-offs was selected in preference to the tertiary filtration. The effluents from the two plants are co-mingled and a single discharge permit then serves both plants.

Some notes on the Coors operation—technical, management, and political—may help to understand better the field of industrial wastewaters:

- First, equalization basins are common to industries subject to batch discharges. The basins are aerated to maintain aerobic conditions and to minimize the deposition of solids. Equalization basins have been advocated for municipal treatment but they have not become assimilated into practice.
- Second, the pure oxygen provides a higher reaction rate and thus smaller aeration basins (i.e., a smaller “footprint,” important in the Coors case).
- Third, the filtration process was used originally at Coors to provide a buffer to ensure compliance with the 30/30 permit.
- Fourth, the Miller-Coors Brewery is highly visible because of its size and because of its historical prominence in Colorado. Any noncompliance with environmental standards, particularly on Clear Creek that receives the discharge from Coors, is noted quickly by the news media. The selection of processes and technologies for the treatment train reflects these political factors, i.e., to ensure compliance at a high probability level.

- Fifth, the management philosophy is the most important facet of how an industry deals with its environmental issues. Coors (now Miller-Coors) has had a history of identifying potential issues ahead of the public perception, political movements, and legal mandates, and dealing with them as matters of good business and good citizenship (some call this being “proactive”), which has been the position of many industries, as opposed a perception by some that they all are “foot-dragging.”
- Sixth, as a rule, industries want to know the rules and to know that the rules are enforced fairly upon their competitors as well, and to have confidence that there will not be vacillation (i.e., that the rules do not vary from year-to-year as political administrations change).

1.4.2.1.2 Anheuser-Busch Brewery

The Anheuser-Busch Brewery in Fort Collins, Colorado, was put on line about 1986. The brewery is located about 16 km (10 mi) northeast of the City, adjacent to Interstate 25 and in an area that is largely irrigated agriculture. Prior to coming to Fort Collins, an agreement was developed with the City of Fort Collins to utilize its south WWTP, constructed in 1968 and largely mothballed in 1976 after construction of a new plant on the same site, i.e., the North Plant (further modified in 1993). The South Plant was renovated in 1986 to accommodate the brewery wastes and was comprised of primary settling, activated sludge, and secondary settling. A bar screen was located at the plant site. As an alternative to the Fort Collins South Plant, the brewery can discharge to a land treatment site. The site is located about 8 km (5 mi) east of the plant. The site has storage and is set up to spray irrigate the wastewater on the land. The spray irrigation rate does not exceed the infiltration rate of the soil. The system is utilized irrespective of crop growth cycles but is suspended during cold months when freezing may be a problem.

1.4.3 INDUSTRIAL PROCESS WATER TREATMENT

Industrial water treatment for process water is another significant area. The variation may include industries that can use potable water directly without further treatment, such as for food products, with perhaps dechlorination. The electric energy industry requires mineral-free water for boiler feed, while the electronics industry requires essentially molecular water. The unit processes in each case may require many of those listed in Table 1.1 (and in Tables 1.2a and b).

1.4.4 HAZARDOUS WASTES

Contaminated groundwater is a common context for hazardous wastes. In some instances, the remedial action is to pump the aquifer and pass the flow through a treatment plant, which is called a “pump-and-treat” situation. Organic chemicals are common contaminants and there are thousands of possibilities. Adsorption by GAC is a common unit

process/technology. Other situations, such as at mine drainage site, may include heavy metals in which case precipitation is a likely unit process. In some cases, hyper-filtration is added, mainly for redundancy.

1.4.5 HAZARDOUS WASTES: IN SITU TREATMENT

In some cases, in situ treatment is applied. A main technical problem is to get the reactants in contact with one another, i.e., how to “transport” one reactant on the surface to another that is “in situ” is the issue. This may involve an elaborate scheme, in which the “transport” is by convection and diffusion. An example is the practice of punching the ground surface with a grid of holes used to pump water with a “reactant” to the site of adsorbed (on soil) or dissolved (in pore water) contaminants. The “reactant” may be a bacterial species (perhaps genetically modified), chemicals, air, steam, etc. The point is that the “reactor” is the in situ site of the contaminant; actually, it is one of numerous micro-reactors.

1.5 DESIGN

A variety of nontechnical issues are a part of any design. Some are addressed in this section. The technical design itself is not just a computational algorithm, but involves mostly assumptions, judgments, and decisions. An engineering background gives the technical basis for decision-making, e.g., what may be feasible, and a context for continued learning.

1.5.1 FACTORS: NONTECHNICAL

The end product of the design process is a physical plant. The plant design is designed by a consulting engineering firm with qualified staff. The firm selected is usually one of several who may have competed for the contract. Based upon the design, a contractor is selected, with the engineer acting as the owner’s agent (the traditional arrangement). Getting to the point of a completed design involves a host of issues that may involve politics, dealing with neighbors, financing, owner’s ideas, operation, esthetics, environmental considerations, water rights, etc. The consulting engineer manages these factors based upon experience and exercise of judgment, as opposed to academic studies.

1.5.1.1 Operation Issues

Design involves a stream of decisions involving “trade-offs” between capital cost and operation. Operation factors may include costs, such as energy and maintenance, the ease of operation, environmental impacts, etc. In addition to such factors, operators nearly always have views that may be important in the design. Some examples include adding a gullet with drain in a pipe gallery for easy hose-down and cleaning; using aluminum hand rails so that painting is not required; venting enclosed spaces and rooms that may be handling chemicals; dehumidifying a pipe gallery; providing attractive lunchrooms and locker rooms with showers; taking

into account noise problems associated with pumps; designing rooms with windows; placing signs to accommodate visitors and public tours, a reception area, etc.

1.5.1.2 Managing a Team

In addition to the management of staff, the engineer assumes the *de facto* leadership and management of an informal team that may include the owner and perhaps a representative from the political body, operators, regulatory authorities, equipment manufacturer’s representatives, the suppliers of materials required in operation, the contractor, the architect, a landscape architect, a water rights expert, a limnologist, security advisor, accountant, financing expert, etc. Those in the team involved depend upon the size of project and its context. As a rule, these ideas are learned by the engineer “on-the-job.” Academic courses tend to focus on technical factors, albeit there are exceptions (see, e.g., Qasim et al., 2006). Excerpts from an article by Lagnese (2000), a former president of the Water Environment Federation (1968–1969), and of the American Academy of Environmental Engineers (1991), who taught a practical design course at the University of North Carolina, provide a firsthand design perspective.

Notes from Joseph F. Lagnese, Jr.

Design is an arduous, iterative process. Ideas are advanced based upon limited factors and intuition and then evaluated. The initial ideas are then refined and/or eliminated, new ideas proposed, and the process repeated as often as necessary to ultimate completion. Stated in another way, design is inherently a “two steps forward, one step backward” process. . . . the ultimate products of design are the plans and specifications required to guide the construction of a total facility that is efficient in operating needs and performance capability. Whereas process design theory and fundamentals require mathematical and science capabilities, the other aspects of design rely upon creative and organizational talents and team-play ability, as well as aptitudes in such diverse areas as economics and aesthetics. Design is a knowledge intensive process which requires not only an understanding of many diverse fundamental concepts, but also such practicums as engineering pricing, selection of process equipment and construction materials, architecture, construction techniques and procedures, operational requirements, ergonomics, satisfying relevant regulatory controls, and project financing. As such, design is an optimization process dependent on the appropriate consideration of a broad range of impacting factors. There are few absolutes; most completed designs represent imperfect solutions.

1.5.1.3 Expansion

The provision for expansion may be done by sizing pipes and the procurement of land for a projected ultimate build-out. Not to plan ahead may result in several largely independent plants on one site, each with its own idiosyncrasies of operation, not to mention inordinately higher costs.

1.5.1.4 Esthetics

Esthetic issues are as important as the functional design, and are often overlooked. Does the plant enhance its sight? Does it fit the

sight architecturally? Was a landscape architect involved? Are persons working at the plant motivated when they enter the premises? Do the mayor and council view the plant with pride? Are peers pointing to the plant as a showcase for the industry? Esthetic appeal is sometimes discounted by designers and owners. Community pride is nearly always associated with public facilities, not to speak of operator morale.

1.5.1.5 Regulations

There are two aspects to regulations: (1) those that specify effluent requirements, and (2) those that specify design. Compliance with the former is essential. Variance is provided for the latter subject to reasonable rationale or pilot plant results. Design guidelines by state regulatory agencies are sometimes controversial. At the time such guidelines were instituted, which go back to the 1930s and possibly earlier, the art of plant design was not very far along. At that time, most of the expertise regarding design resided among the engineering staff of the state health departments (Ongerth, 1999). As educational institutions developed a cadre of professionals in the field, however, the design capabilities expanded among those in consulting engineering.

1.5.1.6 Institutions

An “institution” is defined here as a “device of society to manage itself” (my interpretation of the term based upon frequent use by a sociologist colleague). Among the institutions in environmental engineering one might include: laws and regulations, the traditions of excellence, practice and lore, education, training, certifications, the licenses to practice, manufacturers, research, government laboratories, the awarding of degrees, construction companies, consulting engineering firms, etc. The respective purposes of these institutions are primarily technical, but they function in a social context.

1.5.1.7 Consulting Engineering

Consulting engineers design systems that provide water supply, treat drinking water, industrial wastes, and municipal wastewaters, and assess the impacts of discharges on receiving water. Any task that contributes to a solution to an environmental problem is within the purview of practice. Consulting engineering has long been regarded as the citadel of technical expertise, ethics, and professionalism. Many consulting engineering firms and engineers within various firms have had careers that match this description.

To give a sense of the nature of consulting engineering and the practitioners, Box 1.2 provides a glimpse through the 70-year career of Harvey F. Ludwig. Box 1.3 describes some of the changes in the character of consulting engineering practice that has evolved since about 1980, i.e., as interpreted by the author. Box 1.4 adds commentary about a “golden” age of environmental engineering that coincided largely with the environmental movement, also as interpreted by the author. These are not the only views of these three areas and are likely to induce alternative or complementary perspectives from others.

BOX 1.2 HARVEY F. LUDWIG ENVIRONMENTAL ENGINEER CONSULTANT

On May 29, 1965, Harvey F. Ludwig (b. 1916) was awarded a doctorate by Clemson University. The citation read, in part,

engineer, teacher, public servant and world-renown authority on environmental and sanitary engineering, his advancement of the engineering profession in the field of environmental health, his scholarly research, and his outstanding leadership in scientific affairs on a national and international basis.



Harvey F. Ludwig, c. 1968

The citation was at year 27 of what has become a 70-year career of continuing contributions and leadership that has helped shape the modern practice of environmental engineering. Dr. Ludwig obtained his BS degree in 1938 in civil and sanitary engineering from the University of California, with MS in 1941. During World War II Dr. Ludwig was a commissioned officer of the U.S. Public Health Service (USPHS). In 1946, he started a consulting practice and in 1949 became an associate professor at the University of California. In 1951, he became Assistant Chief Engineer, USPHS (under Dr. Mark Hollis). In this position, he presided over the development of the institutions (i.e., laws, federal agencies, programs) that were the foundations for what emerged in final form in the 1970s (and have continued to evolve). At the same time, Dr. Ludwig oversaw research funding at various universities across the United States that fueled research and graduate programs that led to a “flowering” of the field that has continued. In 1956, Dr. Ludwig resigned from the USPHS and started Engineering-Science (ES). His *modus operandi* was to hire mostly MS and PhD students recruited from his network of academic colleagues who would adapt their research knowledge into practice. At that time, hiring engineers with graduate degrees was more unusual than common.

BOX 1.2 (continued) HARVEY F. LUDWIG ENVIRONMENTAL ENGINEER CONSULTANT

ES expanded rapidly with offices at key cities in the United States including a research laboratory and office in Oakland (c. 1956), and later in Washington, District of Columbia (c. 1966) headed by his long-time USPHS associate, Gordon MacCallum, and then in Austin, Texas, started by Dr. Davis Ford (c. 1968). The firm grew rapidly with important projects throughout the United States and started to develop an international clientele. Dr. Ludwig was at this time, in 1969, a “legend” in the field. At the same time, the field was experiencing a “golden age,” i.e., research was advancing knowledge, graduate programs were spreading, practice was flourishing, and the public had adopted a widespread environmental ethos that was being translated by politicians into laws and policy. At that time, ES was arguably at the crest of this movement, i.e., one of the most visible of firms in the field and at the forefront of innovation. This was due not only to Dr. Ludwig individually, but to the way he had structured the firm with both depth and breadth of expertise and leadership. In addition, Dr. Ludwig had extensive involvement with professors from throughout the United States.

ES was actually, however, a part of a larger corporate structure. One entity was a construction company that had financial difficulty (due to a low bid on a dam). The “way-out” was a buyout offer in 1968 by Zurn Industries of Erie, Pennsylvania. The new corporate structure did not work out, and Dr. Ludwig left the firm in 1972, setting up his own practice in Washington, District of Columbia (Ludwig 1985). ES was later purchased by its employees and remained prominent in the field through 2004 when its identity was assimilated fully by Parsons, an international construction company.

In 1973, Dr. Ludwig’s private practice led to Bangkok where he started a new firm, Seatec International, which has influenced environmental engineering throughout South-East Asia. While there, he has championed the case for adapting environmental standards and designs to match the socioeconomic context of developing countries, i.e., as contrasted to imposing the design approaches of industrialized countries. As of 2008, Dr. Ludwig had some 358 publications ranging from research on coagulation, c. 1941, to strategies for saving the forests in South-East Asia, c. 2005. Four of his papers won awards from organizations such as ASCE, AWWA, WEF. Personal achievement awards have included election to the National Academy of Engineering, in 1969, shortly after its founding; the AEESP Founder’s Award; the AAEE Honorary Member award; the 1999 University of California College of Engineering Alumnus of the Year; and various awards in Bangkok.

As to the persona, Dr. Ludwig has been a mentor to countless engineers in practice. He is known by his high standards in writing, in professional practice, and in getting a job done. To quote Professor Donald Anderson, c. 1965, when he headed the Oakland office of ES, “When you work for Harvey Ludwig,...,” meaning that much was expected. He was instrumental in founding what is now the American Academy of Environmental Engineers (a certifying organization), c. 1956, and sponsored the founding of the Association of Environmental Engineering and Science Professors (AEESP), c. 1963. In 1966, his firm ES initiated the sponsoring of a “best thesis” cash award within AEESP; his rationale was that the significant cash (\$1000 at that time) added prestige to the award. The award has continued under auspices of other firms with inclusion of both master’s and doctoral theses.

Dr. Ludwig is known for expressing his candid opinion (on virtually any topic). Consequently, he has both many admirers and a few detractors. He continues an active correspondence, by e-mail, with perhaps a circle of some 20–100 family members, friends, and colleagues. From Bangkok, Dr. Ludwig remains a presence in the field of environmental engineering.

BOX 1.3 GLOBALIZATION OF THE WATER INDUSTRY AND CONSULTING ENGINEERING

In 1974, the water industry in England and Wales was reorganized with 10 regional water authorities with jurisdiction over all water functions, e.g., water supply, wastewater, flood control, and river management. The regional authorities had taken over from some 1600 separate local authorities (Okun, *pv*, 1977). In 1988, due to a change in political climate, let by the then Prime Minister, Margaret Thatcher, the water industry in England and Wales was again “privatized,” with the 10 water authorities remaining. The change had a global significance. Using Thames Water as an example, which was one of the 10 regional water authorities, the organization was freed from the limitations of being a public entity. Over the years following privatization, Thames Water purchased major companies in the water industry and sold its services worldwide in consulting engineering, management, construction, and operation (see <http://www.thameswater.co.uk>). They joined Vivendi Universal of France in providing “one-stop shopping” for water services. Vivendi Universal was formerly Compagnie Generale des Eaux created in 1853 by imperial decree to provide water to Lyons. The company expanded and diversified from 1980 to 1996,

(continued)

BOX 1.3 (continued) GLOBALIZATION OF THE WATER INDUSTRY AND CONSULTING ENGINEERING

becoming involved in music, publishing, TV and films, telecoms, environmental services, etc. The name was changed in 1998 to Vivendi Universal. The environmental services include the divisions of water, waste, energy, and transportation, and were active in over 100 countries. Water customers number about 110 million. The creation of Thames Water and the expansion of Compagnie Generale portended fundamental change in the character of consulting engineering. The “client” became a “customer,” something not thinkable until the 1980s.

In the United States, the way had been paved legally for this “new age” institutional form, i.e., a multinational conglomerate. In 1972, the U.S. Justice Department forced ASCE, under consent decree, to change its code of ethics to permit bidding for services and to permit advertising. The upshot was that during the 1980s, bidding for design services became the norm for some clients (not all joined this trend). To compete in the new market place, some of the larger consulting engineering firms formed subsidiary companies to construct and operate plants. The traditional engineer–client relationship was being replaced by “turnkey” projects based on bidding. With this institutional metamorphosis, U.S. engineering firms were then poised to compete globally with Thames Water and Compagnie Generale des Eaux. Professional practice was no longer protected by ethics, tradition, and law. Engineering services were not the same; they were becoming a commodity.

BOX 1.4 GOLDEN AGE OF ENVIRONMENTAL ENGINEERING

Almost every field has a “golden age,” perhaps characterized by the nostalgia of those who reminisce. In October 1957, the then Soviet Union launched into orbit the earth satellite *Sputnik*. This event electrified the world and shocked the United States in almost every respect. One could easily view *Sputnik* moving across the skies relative to the field of stars as tangible evidence that the United States was not so advanced as presumed; the view evoked deep emotions. The upshot was introspective questioning of the adequacy of U.S. education, science, mathematics, and engineering. The result was the unprecedented funding of these areas, perhaps epitomized by the 1961 commitment of President Kennedy to “place a man on the moon within this decade.” At the same time, an environmental movement was in a period of gestation. In 1962, Rachael Carson’s *Silent Spring* was published

and set in motion the movement, which had continuing momentum through the 1970s, and was more or less dissipated by the 1980s, perhaps as the political climate was changing; at the same time, the movement was gaining ground in other countries. A series of laws and policies grew out of the movement, however, along with public funding for research, education, and mandates for cleaning up the environment and an associated flourishing of environmental engineering practice. Also, during this period, i.e., in the early 1960s, doctorates became a requisite for academics in engineering and the number of graduate programs expanded beyond the “handful” that had existed up to about 1960. Funding for research was appropriated by the U.S. Congress and the chances for funding was higher in 1960s than in later decades. The result was a science-based understanding of many of the unit processes that was translated toward a more rational practice. Some of the processes that were delineated in scientific terms included the concept of an activated-sludge basin as a “reactor,” and the associated materials-balance depiction; reaction rates described in terms of “kinetics”; the adoption of the Michaelis–Menten description of bacterial kinetics; the assimilation of biochemistry in understanding biological reactions and the role of ATP as well as DNA; the assimilation of turbulence theory in understanding coagulation and flocculation; the introduction of chemical equilibrium theory and its application as a basis for understanding processes, e.g., in coagulation, redox reactions, precipitation, acid–base reactions, ion exchange, etc.; the assimilation of physical chemistry as a basis for understanding the role of temperature on reaction rate, the mechanisms of molecular adsorption on activated carbon, the laws for gas transfer, the role of osmotic pressure in membrane desalination, etc.; anaerobic reactions became understood in terms useful for practice. In addition, the “Advanced Waste Treatment Research” program was initiated in 1962 by the Division of Water Supply and Pollution Control, USPHS, which included processes such as adsorption, electrodialysis, distillation, reverse osmosis, ion exchange, etc., with funding for both in-house and extramural projects. The program also contributed to the changing paradigm of the field, i.e., from empiricism to science.

The research during the 1960s was, to a large extent, “unsolicited,” meaning that a professor could propose the topic and the approach; the “peer-review” scrutiny was the basis for quality control. This contrasted with the approach after 1972 when EPA was formed and research funding had to “support regulations.” The research objectives were formulated by persons within a given agency, which greatly limited continued progress in applying fundamental knowledge to applications. The National Science Foundation, however, remained a traditional unsolicited research organization,

BOX 1.4 (continued) GOLDEN AGE OF ENVIRONMENTAL ENGINEERING

but with not too much funding available in environmental engineering. Some topics remained without “closure” and the rate of advance to the field was slowed and dependent, to a large extent, on what could be gleaned from projects that suited the agencies, particularly EPA. Although the “golden age” has passed, the profession has made the transition from purely empiricism to rational approaches. Some may argue that the pendulum has swung too far, i.e., that we may lack a sense of serving professional practice as the primary guide in engineering education and perhaps even in consulting engineering.

1.6 SUMMARY

As indicated, water treatment covers a great deal of variety. With about 15 unit processes, the combination selected for a treatment train depends on the technical requirements of the treatment task, i.e., the contaminants to be treated and the objectives of the treatment.

For any unit process, a number of technologies exist or may be developed that utilize the principles of the process. Some are generic and some are proprietary. The technologies provide an array of choices that help to tailor a treatment train to the situation at hand.

The intent of the book is to describe theory and practice for each of the unit processes. The specific technologies are described only as useful to illustrate the processes. The technologies represent the variations of principles associated with a particular unit process.

Nontechnical issues play a part in almost every technical decision and are alluded to in order to indicate some of the realities of process design. These factors are learned mostly in the context of experience and are mentioned in this book only to a limited extent so that there is an awareness of their role.

PROBLEMS

1.1 Unit Processes

Visit a treatment plant and describe your impressions about the plant and its unit processes. (The idea is to gain some familiarity with a plant and to experience the scale, appearance, functioning, etc. of unit processes. Later, you can compare the variation in technologies between plants.)

1.2 Unit Processes and Models

Based upon your recent visit to a WTP, list the treatment processes that you observed. Did you see any physical models? What were the purposes?

1.3 Sampling and Instrumentation

Regarding your visit to a water (or wastewater) treatment plant in your vicinity, describe and distinguish

between process control and surveillance? What online instruments did you see? What about sampling? Was sampling discussed? What kind of sampling? Was laboratory analysis discussed?

The following problems, Problems 1.4 through 1.14, are intended to illustrate a variety of treatment situations that may be encountered in practice.

1.4 Treatment Trains

Suggest treatment trains for a five star hotel located in Cyprus for (a) drinking water, (b) wastewater.

1.5 Treatment Train

Describe a traditional treatment train for a municipality that treats surface water.

1.6 Water Quality

A small city relies on groundwater. Suggest some water-quality issues that could be present and unit processes that could deal with the issues.

1.7 Treatment Train for Potable Water

Describe the treatment train that produces potable water for your locale.

1.8 Treatment Train at WWTP Site Visit

Describe the treatment train for wastewater that you visit in your locale.

1.9 Potable Water Quality Goals and Treatment

Discuss the future water-quality issues and associated treatment modifications for potable water for the plant in your locale.

1.10 Water-Quality Goals and Wastewater Treatment

Discuss the future water-quality issues and associated treatment modifications for wastewater in your locale.

1.11 Technologies for Unit Processes

Generate a list of technologies for each of the unit processes identified in your visits to treatment plants (pick two for hand-in).

1.12 Ambient Water-Quality Processes

In the ambient environment, list cases in which water-quality changes occur passively. Is knowledge of unit processes applicable to understanding natural systems? Discuss.

1.13 Passive versus Active Technologies

Discuss passive technologies versus active (i.e., in which operation is essential to performance). List examples.

1.14 Groundwater Contaminants

List 12 contaminants that might be found in a pump-and-treat situation.

1.15 Form-Fit Context

Select several kinds of treatment situation that could include any of a variety of possibilities for water-quality profiles and the uses of water. What kind of treatment “fits” would you feel could be appropriate for each hypothetical (or real case from any experiences or knowledge) that you generate.

1.16 Social Context

What different social and political contexts would you expect to encounter in the above treatment situations?

Describe how you would respond with respect to treatment technologies.

1.17 Site Visit to WTP

Visit a WTP, and based upon your visit, comment on any aspect of the plant that you found of interest. This could be related to operation, design, the selection of unit processes for the treatment train, the appearance of the influent water, the appearance of the product water, the particular characteristics of any unit process, the control system, the monitoring, the requirements for product water, etc.

1.18 Site Visit to WWTP

Visit a WWTP, and based upon your visit, comment on any aspect of the plant that you found of interest. This could be related to operation, design, the selection of unit processes for the treatment train, the appearance of the influent water, the appearance of the product water, the particular characteristics of any unit process, the control system, the monitoring, the requirements for product water, etc.

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Regarding Colorado Springs, Jim Phillips and later Daryl Gruenwald hosted many class field trips to the plant during the 1970s and provided brochures and plant descriptions from that period that were utilized in this chapter. Since the 1970s, the main plant has been expanded and the tertiary plant has been modified to eliminate the lime clarification and GAC adsorption, with new rapid filters constructed; the 1970s plant was used, however, for the examples in this chapter since it illustrated the points useful for this introductory chapter. Tony Woodrum and Pat McGlothlin in a May 2001 tour of the facility provided an update of the changes that had occurred since the 1970s. Woodrum, Wastewater Operations Superintendent, gave permission (2010) to utilize photographs of the 1970s plant.

Concerning the boxes, the author requested permission from the late Dr. Harvey Ludwig (1916–2010) to use his biography and photograph, and to provide corrections regarding accuracy. Dr. Ludwig commented (October, 2009) that the summary of ES was accurate, subject to a few minor corrections. The biography was done, however, by the author alone based on a long-time personal knowledge going back, in fact, to 1957 and on Dr. Ludwig's autobiography (Ludwig, 1985).

GLOSSARY

Active process: A process that is controlled by actions of the operator.

Box (n.): A short, often boxed auxiliary story that is printed alongside a longer article and that typically presents additional, contrasting, or supplemental views.

Constant: A ratio of two or more variables that is characteristic of a group of materials or a system. Examples of the former include the universal gas constant for gases, and the modulus of elasticity for solid materials. Often, a coefficient is called a constant.

Discipline: A family-like grouping of individuals sharing intellectual ancestry and united at any given time by an interest in common or overlapping problems, techniques, and institutions . . . Some are happy families, with little controversy over methods and goals. Others are fractured into many research schools, each with a different agenda, each evolving its own traditions of thought and work, and each competing for resources and recognition . . . Disciplines not only lend structure and meaning to lives, they also bring order and significance to knowledge. (Excerpts from the Preface of Servos, 1990.)

Engineered process: A unit process that has been designed by an engineer (as opposed to a natural process).

Natural process: An influence within the ambient environment that causes changes in water quality. Examples include dilution due to mixing of streams, dispersion within a stream, heat transfer involving ambient water, microbiological reactions within an ambient water body, etc.

Passive process: A process that occurs largely without operator intervention. Slow sand filtration or trickling filter treatment are examples. All natural unit processes are passive.

Process: An influence that causes change, i.e., a "state" change. As applied to water quality, a process causes change in one or more water-quality characteristics.

Science: Systematized knowledge obtained from observation, study, and experiment in order to determine the nature of that studied. George A. Olah, 1994 Chemistry Nobel at ACS Symposium as reported in *Chemical & Engineering News*, Vol. 76(35):6, 31 August 1998.

State of water: The quality characteristics of a given water volume, including concentrations of mineral suspended matter, ions, molecules, microorganisms, and such parameters as temperature, pH, specific electrical conductance, etc.

Technology: (1) An anthropogenic device contrived to accomplish a task. The rapid filtration process is encompassed within the filtration technology, which includes all of the appurtenances to make it function to remove suspended particles to a specified concentration level. (2) A collection of devices contrived to accomplish one or more tasks, as in a system. Water treatment technology includes all of the processes and relevant appurtenances to produce potable water.

Technology: A technology is a means to implement a unit process. Any number of technology forms may be devised to embody a unit process. For example, a biofilm reactor may be embodied in several forms, including a traditional trickling filter, a deep-bed trickling filter, a rotating disk reactor, a traditional slow sand filter, a bio-filter for removal of natural organic matter (NOM), etc.

Treatment: Subjecting water to the unit processes of a treatment train.

Treatment train: An aggregation of unit processes.

Unit operation: A term used in chemical engineering to designate a physical change, e.g., pumping, screening, sedimentation, filtration, etc. The term is not used in this book in favor of using a single term, “unit process.”

Unit process (chemical engineering): A term used in chemical engineering to designate a chemical change, e.g., oxidation, precipitation, disinfection, and biological treatment. The chemical engineering literature is not unequivocal in the use of the two terms “unit operation” and “unit process,” but the definitions given seem to capture the sense of how they are used.

Unit process (this book): As used in this book, the term “unit process” means an engineered effect that causes a “state change.” The sense is the same as in chemical engineering except that a “state change” is much broader than being restricted to a “chemical change.” A state change may include not only chemical change, but pressure change, temperature change, concentration change, etc. Thus, settling (change in

concentration of particles) is a process by this definition as is even pumping (which causes a pressure change).

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2 Water Contaminants

Contaminants in water encompass a wide variety of substances. A sampling might include inorganic ions, organic molecules, chemical complexes, mineral particles, microorganisms, and even heat. Larger kinds of contaminants may include oil and scum, natural debris, fish, boards, rags, and whatever may be discarded to the sewer or to ambient waters. Contaminants can number, literally, in the millions. Those that are regulated in the United States number about 4000.

Typical source waters for various purposes include mountain streams, lower reaches of rivers, municipal wastewater, treated municipal wastewater, hazardous waste sites, etc. Each has a typical “profile” of water quality, and some kind of treatment is always required prior to use in order to meet the criteria or standards of that use. Then, after a use of water, and prior to discharge to rivers, lakes, and seas, the product water must meet the standards and/or criteria established for such discharge. The treatment train selected depends upon the particular combination of source water available and product water required. The source water quality available and product water quality required, along with cultural, economic, and operation factors, is the treatment “context.” Thousands of such combinations are possible, making each treatment context unique.

2.1 WATER QUALITY: DEFINITIONS

The term *water quality* has to do with the description of given water in terms of its *characteristics*. Characteristics of water quality include temperature; concentrations of various kinds of particles; concentrations of dissolved materials; and parameters such as turbidity, pH, color, conductivity, etc. The term *characteristic* is more inclusive than the term *contaminant* and would include temperature, color, turbidity, conductivity, etc. Two of these categories of characteristics, i.e., particles and dissolved materials, would include thousands of species each. A particular combination, or *set*, of characteristics would comprise a water quality *profile*. Those contaminants that interfere with a particular use may be considered pollutants.

To add further to the definitions that circle about the same idea, the term *parameter* is used frequently. Water quality parameters might include temperature, BOD, pH, specific electrical conductance, UV_{254} absorbance, etc.

With respect to uses of water, the terms *criterion* and *standard* are important. A water quality *criterion* is a contaminant concentration *limit* that, if exceeded, may impair a use or cause a toxic effect in certain animals or plants. As an example, a boron *limit* of 0.5 mg/L is considered appropriate for citrus crops. A criterion could also specify a contaminant or

parameter *range*, e.g., $3.3 \leq \text{pH} \leq 10.7$ for trout (McKee and Wolfe, 1963, p. 236). A water quality *standard* is a quasi-legal limit for a contaminant concentration or parameter value, i.e., the value may be referenced in a law but may be either “recommended” or “enforced,” depending upon the severity of the effects and the levels that are economically achievable. Usually, there is nothing absolute about the foregoing definitions.

Table 2.1 illustrates a water quality description for a proposed industrial waste discharge. Points of interest in Table 2.1 are (1) some 37 contaminants are listed; (2) concentration limits are shown for each contaminant; (3) two places for discharge—a publicly owned treatment works and a river—are shown, each with its own respective discharge limits; (4) limits are given in terms of the monthly average and the daily maximums; (5) a variety of organic compounds are listed; and (6) a variety of heavy metals are listed. Each treatment situation is different and would have a different list of contaminants and different limits. A similar tabular description, but with different constituents, would apply to a municipal wastewater discharge, a drinking water treatment plant product water, or another industrial waste situation.

2.1.1 CONTAMINANTS

A *contaminant* is defined as a substance that makes another substance impure. As applied to water, any material that is present in the water other than molecular water would be a contaminant. Often, the term has a negative connotation; in other words, we most often refer to an undesired substance as a contaminant. The term’s *constituents* and *characteristics* have more neutral connotations and are used here almost interchangeably with the word contaminant. As noted, however, the term *characteristic* is more inclusive and would include such things as temperature and turbidity.

A *pollutant* is a synonym of the word *contaminant* but is more often identified as an *introduced* contaminant from an anthropogenic source. The definition of a pollutant by the US Public Health Service drinking water standards (USPHS, 1962) was

Pollution, as used in these Standards, means the presence of any foreign substance (organic, inorganic, radiological, or biological) in water, which tends to degrade its quality so as to constitute a hazard or impair the usefulness of the water.

As used later by the regulations pursuant to PL92-500—the 1972 Clean Water Act—the term *pollutant* is associated with an introduced contaminant and implies impaired utility of water.

BOX 2.1 ON WATER QUALITY

In the 1880s, notions of water quality were limited by the knowledge in the two of its science “mother” fields—chemistry and bacteriology. Inorganic constituents were expressed as concentrations of various salts, e.g., calcium sulfate, sodium chloride, etc. Many years would elapse before inorganic chemical water quality would be expressed in terms of cations and anions, e.g., as Ca^{2+} , SO_4^{2-} , etc. The ion theory had not yet taken hold, being proposed only in 1887 by Svente Arrhenius (1859–1928), professor of chemistry, University of Uppsala, but not accepted until years later. Regarding microbes, the science of microbiology was just being defined, based upon the work of Pasteur in 1861, Lister in 1867, and Koch in 1876 and 1882 (Prescott et al., 2005, p. 8). By about 1882, the science of bacteriology had an identity.

Courses in “sanitary chemistry” that evolved from this background were focused largely on wet chemistry analysis of such constituents as alkalinity, hardness, nitrate, chloride, nitrogen, biochemical oxygen demand (BOD), etc. The Langelier Index, proposed by Professor Wilfred Langelier in 1936 (see Langelier, 1936), brought some degree of rationale from equilibrium chemistry to the problems of deposition of calcium carbonate and corrosion in pipes. The index was applied empirically to handle problems of practice. Much about bacterial growth and enumeration of bacteria was understood by the early twentieth century. Such was, in-a-nutshell, the state of knowledge of water quality about 1950.

By the early 1950s, the stage was being set for the modern era. The book *Water Quality Criteria* (McKee, 1952) was published by the State of California, microbiology fundamentals were assimilated in academic studies, and Werner Stumm at Harvard introduced the idea of equilibrium chemistry as a means to model the behavior of natural systems. By the late 1950s, instruments such as atomic absorption, gas chromatography, polarography, fluorescence, TOC analyzers, mass spectrograph, etc. were introduced.

By the 1960s, ideas from chemistry theory, e.g., thermodynamics, kinetics, redox reactions, acid–base reactions, complexation, etc., became assimilated into the nomenclature of aqueous chemistry. Analyses of water could include a complete spectrum of organic compounds along with the traditional ones. Total organic carbon (TOC) was a parameter used to supplement BOD but has yet to supplant the latter. Instrumental methods were displacing wet chemistry and providing the means to analyze for virtually any contaminant, and at microgram per liter levels.

By the 1980s, the idea of water quality had moved well beyond the traditional notions prevalent in the 1950s. Also, the spectrum of contaminants was very broad and might well have included more than 100 in a typical analysis. Because of both perceived health risks and analytical capabilities that included more compounds and at lower levels, the number regulated increased to several thousand contaminants.

2.1.2 STATE OF WATER

The *state* of a volume of water, as defined here, refers to its water quality. Characteristics of water quality that may comprise its “state” include temperature; concentrations of various kinds of particles; concentrations of dissolved materials; and parameters such as turbidity, pH, color, conductivity, etc. The idea of “state” (defined usually, in the field of physical chemistry, as pressure, temperature, volume) comes from the field of physical chemistry and is the same as a water quality “profile.” Both water quality “state” and water quality “profile” are terms adopted for use in this text.

The term water quality “state” adds the notion that energy is involved. For example, if we reduce the concentration of a substance, as done by a unit process, a state change results and energy is required.

2.1.3 CRITERIA

A water quality *criterion* refers to a contaminant level, which when not exceeded, will not impair a given beneficial use of water. A great deal of research and deliberation is involved in establishing a criterion for a particular contaminant. Seldom is the result definitive, and considerable uncertainty may be associated with any numerical value determined.

2.1.4 STANDARDS

A criterion becomes the basis for a *standard*, which is a codified criterion. Water quality standards have evolved over the decades of the twentieth century. Usually, standards are *normative* in character, i.e., dependent not only on effects on uses but on economic and cultural factors.

2.1.4.1 Kinds of Water Quality Standards

Water quality standards have been developed for a variety of situations. The first in the United States were in 1914 and applied to drinking water on “common carriers” that crossed interstate boundaries. These standards evolved, incrementally, to the USPHS Drinking Water Standards of 1962. They are useful to review for the following reasons: (1) the standards provide an overview of some of the notions of basic standards for drinking water quality; and (2) the 1962 standards were a starting point for those that have evolved pursuant to PL93-523, the 1974 Safe Drinking Water Act, and its ensuing amendments.

TABLE 2.1**Proposed Discharge Limitations to Illustrate a Variety of Contaminants and Maximum Concentrations for an Industrial Discharge**

Parameter	Discharge to POTW ^a		Discharge to River ^b	
	Monthly Average (mg/L)	Daily Maximum (mg/L)	Monthly Average (mg/L)	Daily Maximum (mg/L)
Anthracene	14	36	11	30
Benzene	33	80	19	70
Chlorobenzene	74	197	8	14
Chloroform	62	176	11	24
Ethylbenzene	108	290	17	56
Toluene	18	45	13	41
<i>trans</i> -1,2-Dichloroethene	19	50	11	28
Tetrachloroethene	40	125	11	29
Trichloroethylene	20	53	11	28
1,1,1-Trichloroethane	17	45	11	28
Methylene chloride	63	241	21	46
1,2-Dichlorobenzene	105	410	40	84
1,3-Dichlorobenzene	108	290	16	23
1,4-Dichlorobenzene	73	194	8	14
Bis(2-ethylhexyl) phthalate	72	197	53	144
Naphthalene	14	36	11	30
Nitrobenzene	1704	4878	14	35
Phenol	14	34	8	13
1,2,4-Trichlorobenzene	109	415	35	72
1,1-Dichloroethene	17	46	8	13
1,2-Dichloropropane	149	605	79	119
2,4-Dimethylphenol	14	36	9	19
4,6-Dinitro- <i>o</i> -cresol	59	211	37	63
Di- <i>n</i> -butyl phthalate	15	33	14	29
Cadmium	130	130	5	11
Chromium, total	120	230	573	1430
Chromium, hexavalent	60	110	132	266
Copper	110	110	<dL	<dL
Lead	400	400	<dL	<dL
Mercury	5	5	0.2	0.5
Nickel	170	360	872	2054
Zinc	490	490	<dL	<dL
Arsenic	50	50	2	4
BOD5	No limits		45	120
TSS	No limits		183	57
pH (standard units)	6	10	6	9

Source: Adapted from Cooper, A.M. et al., *Environ. Prog.*, 11(1), 18, February 1992.

^a Pretreatment limitations to POTW (publicly owned treatment works, per PL92-500, the 1972 Clean Water Act).

^b Direct discharge limitations.

In 1965, PL89-234 required that states develop standards for interstate streams. In 1972, pursuant to PL92-500—the Clean Water Act—an effluent discharge permit was required and was called the National Pollution Discharge Elimination System (NPDES) permit. Drinking water standards were required by PL93-523—the Safe Drinking Water Act—

which was the first federal mandate for states to develop drinking water standards. By 1986, some 83 contaminants were regulated. Regulation of toxic pollutants was required under the 1972 Clean Water Act (PL92-500), resulting in the “priority pollutant” list with some 129 contaminants (Keith and Telliard, 1979). In addition, standards have evolved, or

have been contemplated, for a variety of other situations such as for water reuse for agriculture, water reuse for drinking water, etc.

2.1.4.2 Normative Standards

There is nothing absolute about water quality standards. Such standards are determined both by the degree of perceived risk that a society is willing to accept and by the knowledge of particular contaminants and their effects, i.e., criteria. It is the *norms* of a society that determine which contaminants are of concern and at what levels. Thus, water quality standards are *normative* in nature.

2.1.4.3 Standards as Targets for Treatment

Water quality standards define the performance requirements for treatment plants. A problem is that such standards have evolved and changed over the decades since their inception, i.e., since the 1962 USPHS drinking water standards, constituting a “moving target,” so to speak. Planning a treatment train should, then, build in the flexibility to meet more stringent standards in the future.

The overall “goal” in drinking water treatment has been, since its inception, “to produce a safe, palatable water,” as expressed by the American Water Works Association. Traditional objectives of treatment that support the health goal have been to remove disease-causing organisms. Removal of color, odor, and turbidity has supported the goal of a palatable water. The concern about chemicals that could be carcinogenic has led to additional objectives, first to remove trihalomethane precursors (expressed in the 1974 Safe Drinking Water Act, i.e., PL93-523). This objective was expanded to include removal of disinfection by-products (DBPs). Subsequent to this, in later amendments, the SDWA provided the mandate to remove an array of organic chemicals and metals. Thus, while the goals have remained the same, the objectives defined to achieve those goals have expanded to accommodate increasing knowledge about contaminants, lower detection limits and increased accuracy in sampling and analysis, and more encompassing normative standards.

2.1.5 SURROGATES

Most measures of water quality involve surrogates, i.e., a quantity that is relatively easy to measure and may be used as an index of the quantity of specific interest. To illustrate, two surrogates—turbidity and coliform bacteria—have been institutionalized in their use. Regarding the latter, there are many enteric pathogens, e.g., hepatitis A virus, ECHO 12 virus, Coxsackie virus, polio virus, *Vibrio cholera* bacterium, *Salmonella typhosi* bacterium, *Shigella dysenteriae* bacterium, *Endamoeba histolytica*, *Giardia lamblia* cysts, *Cryptosporidium parvum* oocysts, etc. By definition, “enteric” means that such organisms may be found in municipal sewage. Therefore, the coliform group of bacteria (more specifically, the fecal coliform subgroup) serves as a surrogate for enteric pathogens in general, and such presence would indicate the presence of pathogens. Turbidity is a general indicator of water quality;

a low level of turbidity does not ensure that the water is safe, but a high level is grounds for rejection based on palatability and on the presumption that the water is not safe.

One of the earliest surrogates in wastewater treatment was the 5 day BOD, i.e., BOD₅ (or simply BOD, with the 5 day incubation period understood). The BOD is a measure of biodegradable organic matter. The difference between BOD

TABLE 2.2
Examples of Surrogates in Water Treatment

Surrogate	Measurement
<i>Wastewater</i>	
BOD ^a	Organic matter that is subject to biodegradation by biological treatment
SS ^b	Solids that are subject to settling and that will remain in suspension
MLSS ^c	Total suspended matter in an activated sludge reactor
VSS ^d	Index of suspended matter that is organic carbon
Coliforms ^e	Indicator of the presence of pathogens
<i>Potable water</i>	
Turbidity ^f	Suspended matter $\leq 1 \mu\text{m}$ Index of palatability
Color ^g	Index of palatability Index of TOC, organic matter, and fulvic acids
TOC ^h	Collective or group measure of organic matter
TTHMFP ⁱ	THM precursors
UV ₂₅₄ ^j	Index of TOC and TTHMFP
Coliforms	Indicator of the presence of pathogens
MPA ^k	Indicator of whether protozoan cysts could be present in finished water
Particle counts ^l	Indicator of quality of finished water

^a BOD: Biochemical oxygen demand.

^b SS: Suspended solids as filtered by filter paper.

^c MLSS: Mixed liquor suspended solids is a gross parameter of active biomass and requires oven-drying a sample; MLVSS: mixed liquor volatile suspended solids, is considered more accurate measure of active biomass, but requires a placing a solids sample, after oven-drying, in a laboratory furnace at 600°C to combust the organic solids.

^d VSS: Volatile suspended solids.

^e Coliforms: Bacteria of the coliform group that ferments lactose. Two subgroups of the coliform group are (1) *Aerobacter aerogenes* and (2) fecal coliforms.

^f Turbidity: A measure of the light-scattering property of a liquid.

^g Color: A measure of the color of a water as measured by the cobalt-platinum standard.

^h TOC: Total organic carbon as measured by converting non-purgable carbon to carbon dioxide, which is measured by infrared absorbance.

ⁱ TTHMFP: Total trihalomethane formation potential, which is the chlorine consumption of a given water in mg/L over a specified period of time, e.g., 24 or 96 h.

^j UV₂₅₄: Absorbance of a water sample by an instrument emitting wavelength 254 nm (in the UV range).

^k MPA: Microscopic particulate analysis.

^l Particle counts: Counts of particles in #/mL in the water source being measured.

measurements into and out of a wastewater treatment plant has been a traditional measure of performance. Also, BOD is an index of the impact on the oxygen resources of the ambient receiving water. One factor in favor of adopting such a surrogate is that its use has been institutionalized (e.g., standards have been established, its laboratory protocol is well known, results of monitoring are available for most plants, its interpretation in terms of plant performance or of water quality is clear).

Table 2.2 lists examples of surrogates used in water treatment (both wastewater and potable water). Those that have emerged since about 1980 include TOC, TTHMFP, UV₂₅₄, MPA, and online particle counts. Some surrogates have a history, e.g., TOC became instrumentally feasible in 1965 through instrumentation developed by Beckman Instruments, Inc., which converted organic carbon to carbon dioxide gas, which then was measured by infrared absorbance. A host of other surrogates could be added. A laundry list, not inclusive, might include TDS (total dissolved solids), EC (specific electrical conductivity), hardness as CaCO₃, alkalinity as CaCO₃, TKN (total Kjeldahl nitrogen), MLVSS (mixed liquor volatile suspended solids), etc.

2.2 FEDERAL LAWS

The formal break with the past for the United States with respect to pollution control was in 1965. In 1962, Rachel Carson's book *Silent Spring* (Carson, 1962) precipitated the environmental movement that articulated public concerns about the environment and spawned a host of laws through the 1970s. The Environmental Movement, although historic in itself, was actually a part of a continuum of political events from the Public Health Movement initiated in the early nineteenth century in England and the Conservation Movement of Gifford Pinchot and Theodore Roosevelt in the early twentieth century.

For engineers, the Environmental Movement resulted in a basic shift in objectives for the design of wastewater treatment plants. From about 1920 when wastewater treatment was underway, most statements of ambient water quality standards were merely to eliminate sludge banks in streams, to prohibit floatables, and to maintain slightly aerobic conditions, i.e., 2 mg/L dissolved oxygen concentration. The idea was to utilize the "assimilative capacity" of a given water body. The main pollutants were BOD and suspended solids (SS).

The new ethic, however, as suggested by the 1965 law and made explicit by the 1972 law, called the Clean Water Act, was to eliminate the discharge of pollutants. In addition to the traditional pollutants, nutrients, i.e., phosphates and nitrates, became a concern along with toxic pollutants. The alga blooms of Lake Erie symbolized the nutrient problem, and the term *eutrophication*, which means nutrient-rich, became a household word. In addition, the 1972 law required a NPDES permit to discharge pollutants. The result was a fundamental transformation in the modus operandi in design objectives for engineers and in the regulation of pollutants.

In the field of drinking water, the U.S. Congress passed the Safe Drinking Water Act, PL93-523, in 1974. This was the

first direct involvement of the federal government in drinking water standards—a dramatic break with the past, which was to change the U.S. water industry.

The passage of the Act was precipitated by an Environmental Protection Agency (EPA) report of trihalomethanes (THMs) in New Orleans drinking water and their link to the higher incidence of cancer. The 1986 amendments resulted in another major change, i.e., that 83 substances were listed as drinking water contaminants, with the provision that 25 contaminants were to be added every 3 years. The new ethic of drinking water treatment was articulated by Abel Wolman in a luncheon speech at the 1985 annual conference of the American Water Works Association with the phrase, "if in doubt, take it out." This phrase, coined by the icon in the field, encapsulated a paradigm shift toward articulated objectives in water treatment that had been occurring since the passage of the Safe Drinking Water Act. This shift was similar in character to the shift in water pollution control from the idea of "assimilative capacity" toward the goal of "zero" pollutant discharge (Box 2.2).

BOX 2.2 FEDERAL LAWS ON WATER POLLUTION CONTROL

According to Dworsky (1967), water pollution was a major public concern to the nation's 75 million people at the beginning of the twentieth century. Congress in 1912, however, made the decision to limit its interest to research and technical assistance and to leave to the states the major role in controlling pollution. After the World War II, Congress passed the Water Pollution Control Act of 1948, PL80-845. The Act included financial and technical aid and provision for research and planning. The Act was amended in 1952, 1956, 1961, 1965, and 1966. The 1956 amendment added a phrase, "to establish a national policy for the prevention, control, and abatement of water pollution." The 1965 Act provided for the establishment of water quality standards for interstate streams and other water bodies, giving the states the responsibility, but federal action could be taken in the face of state inaction. The 1972 amendments established the requirement for effluent standards and the National Pollution Discharge Elimination System (NPDES) permit. In 1970, the Environmental Protection Agency (EPA) was established by President Nixon to administer the environmental laws (with some exceptions). The Safe Drinking Water Act was enacted in 1974 by PL93-523 and has had a similar sequence of strengthening amendments.

The federal legislation culminated in the form of the Comprehensive Environmental Response, Compensation, and Liability Act (Superfund) and was enacted in 1980 by PL96-510, spawning an industry on cleanup of hazardous waste sites.

2.2.1 LEGAL DEFINITIONS

As a rule, terms used in federal legislation are defined; many have been assimilated in the general lexicon on water quality. Several are quoted here for reference.

As defined by PL93-523, the Safe Drinking Water Act of December 16, 1974, Section 1401,

(3) The term *maximum contaminant level (MCL)* means the maximum permissible level of a contaminant in water, which is delivered to any user of a public water system.

(6) The term *contaminant* means any physical, chemical, biological, or radiological substance or matter in water.

As defined by PL92-500, the Clean Water Act of October 18, 1972, Section 502, General Definitions,

(6) The term *pollutant* means dredged spoil; solid waste; incineration residue; sewage; garbage; sewage sludge; munitions; chemical wastes; biological materials; radioactive materials; heat; wrecked or discarded equipment; rock; sand; cellar dirt; and industrial, municipal, and agricultural waste discharged into water.

(11) The term *effluent limitation* means any restriction established by a state or the administrator on quantities, rates, and concentrations of chemical, physical, biological, and other constituents that are discharged from point sources into navigable waters, the waters of the contiguous zone, or the ocean, including schedules of compliance.

(12) The term *discharge of a pollutant* and the term *discharge of pollutants* means (a) any addition of any pollutant to navigable waters from any point source, (b) any addition of any pollutant to the waters of the contiguous zone or the ocean from any point source other than a vessel or other floating craft.

(13) The term *toxic pollutant* means those pollutants or combinations of pollutants, including disease-causing agents, which after discharge and upon exposure, ingestion, inhalation, or assimilation into any organism, either directly from the environment or indirectly by ingestion through food chains, will, on the basis of information available to the administrator, cause death, disease, behavioral abnormalities, cancer, genetic mutations, physiological malfunctions (including malfunctions in reproduction), or physical deformations in such organisms or their offspring.

(14) The term *point source* means any discernible, confined, and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal-feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged.

(17) The term *schedule of compliance* means a schedule of remedial measures, including an enforceable sequence of actions or operations, leading to compliance with an effluent limitation, prohibition, or standard.

(18) The term *industrial user* means those industries identified in the Standard Industrial Classification Manual, Bureau of the Budget, 1967, as amended and supplemented, under the category 'Division D—Manufacturing,' and such other classes of significant waste producers as, by regulation, the administrator deems appropriate.

(19) The term *pollution* means the man-made or man-induced alteration of the chemical, physical, biological, and radiological integrity of water.

2.2.2 REGULATIONS

Federal agencies are charged with the responsibility to implement federal laws. This is done in terms of regulations, which are published in the *Federal Register* as proposed rules, and then after sufficient comment period and hearing if needed, a final rule is published. Finally, the regulation is "codified" in the *Code of Federal Regulations (CFR)*. These regulations are "regulatory law" and have the force of law. Parties having an interest in the regulations may comment and influence the outcome as long as the public interest is not compromised. The comments may provide technical data and knowledge that expands the perspective of the agency and provide a forecast of economic impact and other consequences. Other parties may argue for more stringent regulations giving evidence of toxic effects to humans and ecological impacts. Finally, the regulations or their interpretation may be challenged in court (the court ruling is "judicial law").

2.2.3 PRIORITY POLLUTANTS

The Priority Pollutant List originated from Section 307 of PL92-500 (the 1972 Clean Water Act), which required EPA to regulate toxic pollutants. The Priority Pollutant List regulates the discharge of 126 contaminants listed in Section 40, CFR, Part 423, Appendix 2.A. The term "priority pollutant" comes from a lawsuit in 1976 in which the National Resource Defense Fund sued EPA in order to force the regulation of specific toxic compounds. A consent decree resulted from the suit, which forced EPA to accept an additional 65 compounds. The expanded list was incorporated into the 1977 Clean Water Act Amendments, PL95-217, and has become known as the *Priority Pollutant List*. The term "priority pollutant" has become widely used, and so knowledge of its origin helps to understand what is meant.

One outcome was that EPA set numeric limits for 105 water contaminants required by February 1992, listed as follows:

TABLE 2.3
List of Priority Pollutants Regulated by the USEPA

Antimony	Toluene	Hexachlorobutadiene
Arsenic	1,1,1-Trichloroethane	Hexachlorocyclopentadiene
Beryllium	1,1,2-Trichloroethane	Hexachloroethane
Cadmium	Trichloroethylene	Indeno(1,2,3-cd) pyrene
Chromium(III)	Vinyl chloride	Isophorone
Chromium(IV)	2,4-Dichlorophenol	Nitrobenzene
Copper	2-Methyl-4,6-dinitrophenol	N-Nitrosodimethylamine
Lead	2,4-Dinitrophenol	N-Nitrosodiphenylamine
Mercury	Pentachlorophenol	Phenanthrene
Nickel	Phenol	Pyrene
Selenium	2,4,6-Trichlorophenol	Aldrin
Silver	Acenaphthylene	Alpha-BHC
Thallium	Anthracene	Beta-BHC
Zinc	Benzidine	Gamma-BCH
Cyanide	Benzo[a]anthracene	Chlordane
Asbestos	Benzo[a]pyrene	4,4'-DDT
2,3,7,8-TCDD (dioxin)	Benzo[b]fluoranthene	4,4'-DDE
Acrolein	Benzo[ghi]perylene	4,4'-DDD
Acrylonitrile	Benzo[k]fluoranthene	Dieldrin
Benzene	Bis(2-chloroethyl) ether	Alpha-endosulfan
Bromoform	Bis(2-ethylhexyl) phthalate	Beta-endosulfan
Carbon tetrachloride	Chrysene	Endosulfan sulfate
Chlorobenzene	Dibenzo[a,h]anthracene	Endrin
Chlorodibromomethane	1,2-Dichlorobenzene	Endrin aldehyde
Chloroform	1,3-Dichlorobenzene	Heptachlor
Dichlorobromomethane	1,4-Dichlorobenzene	Heptachlor epoxide
1,2-Dichloroethane	3,3'-Dichlorobenzidine	PCB-1242
1,1-Dichloroethylene	Diethyl phthalate	PCB-1254
1,3-Dichloropropylene	Dimethyl phthalate	PCB-1221
Ethylbenzene	Di-N-butyl phthalate	PCB-1232
Methyl bromide	2,4-Dinitrotoluene	PCB-1248
Methyl chloride	1,2-Diphenylhydrazine	PCB-1260
Methylene chloride	Fluoranthene	PCB-1016
1,1,2,2-Tetrachloroethane	Fluorene	Toxaphene
Tetrachloroethylene	Hexachlorobenzene	

Table 2.3 lists the contaminants regulated under Section 307. Of equal importance, the list gives a sense of the variety of metals and organic compounds considered toxic above certain threshold concentration limits and that are subject to treatment. In other words, the idea of a pollutant had been expanded well beyond the traditional notions, prevalent till about 1960, that BOD and SS were the main concerns.

2.3 MATURATION OF WATER QUALITY KNOWLEDGE

From the beginning, before about 1900, knowledge of water contaminants evolved based upon developments that included (1) the mother sciences—chemistry and microbiology, (2) public mandates related to water quality standards, (3) specific knowledge about water contaminants and their ecological and health effects, (4) criteria for various kinds of uses of water,

and (5) analysis methods that provide measurement capabilities to nanograms per liter. Thus, the state of knowledge, although not complete, has come a long way from the inception of the modern era of water treatment, i.e., since about 1880 (Box 2.3).

2.3.1 KNOWLEDGE OF CONTAMINANTS

The first formal compilation of substances that comprise water quality was the 1952 book *Water Quality Criteria* by Professor Jack McKee of Cal Tech (and Partner, Camp, Dresser, and McKee), commissioned by the State of California. The book was revised and expanded by Harold Wolfe in 1962. It was an exhaustive treatise on substances that may be found in water and the effects of different concentrations. A similar book called the *EPA Yellow Book* was published in 1973 (USEPA, 1973), which had a wider distribution.

BOX 2.3 THE IONISTS

To give an idea of how recent the notion of water quality has been, the idea of expressing concentrations of mineral substances in terms of ion concentration did not catch on until after about 1900 (and certainly not before 1890). By about 1890, Svante Arrhenius of Uppsala, Jacobus Henricus van't Hoff at Amsterdam, and Wilhelm Ostwald at Leipzig had formulated a comprehensive theory of solutions and became known as the "Ionists" (from Servos, 1990, pp. 13–43).

To put in perspective the ionic theory of solutions, the notion at the time was that a salt in solution retained its identity as an undissociated compound. Thus, compounds in solution were called sulfate of alumina, sulfate of calcium, chloride of sodium, etc., and not as ions, e.g., Ca^{2+} , Cl^- , SO_4^{2-} , etc. The ionic theory was not embraced with enthusiasm as one might expect (e.g., being a conceptual "breakthrough"), but rather with skepticism and doubt. The ionic theory displaced the prevailing notions of solution only gradually, with tradition hanging on for several decades after discovery. The practical significance is that if we are interested, for example, in water quality data c. 1900, we must be prepared to deal with the old expressions.

2.3.2 MEASUREMENT TECHNOLOGIES

Prior to 1960, coliforms, turbidity, and pH were the main concerns in drinking water, along with selected anions and cations—mainly those associated with hardness and alkalinity. Water supplies with heavy metals were avoided. Chlorine was an added constituent that required measurement. In wastewater, BOD and SS were the main concerns (after floatables, scum, oil, and settleable materials). The coliform density was measured by the most probable number (MPN) method, which was supplemented about 1960 by the membrane filter method. Cations and anions were measured by traditional wet chemistry methods involving titrations to some end point or conversion of a given substance to a colored complex that followed the Lambert–Beer law and could be measured by a spectrophotometer. The Jackson tube measured turbidity; this was a tube with gradations, which was filled with water until the light from a candle at the bottom was extinguished. The reading was stated as Jackson Turbidity Units (JTU).

By the early 1960s, a major technological revolution was underway in instrumental analysis. The TOC analyzer was developed, along with the atomic absorption instrument for metal ions, the gas chromatograph for organic compounds, polarography for specific ion probes, and the mass spectrograph for any compounds. While these instruments became available technologies in the 1960s, they were not used widely in water treatment until years later. These instruments developed further in the 1970s in the degree of sensitivity, and soon measurement in the range of micrograms per liter

became feasible (such as in gas chromatography). The ability to measure organic compounds at concentrations in the range of micrograms per liter made possible the development of water quality standards in the same range.

2.4 CATEGORIZATIONS OF CONTAMINANT SPECIES

Contaminant species number in the millions. Such a large number of species must be dealt with in terms of a classification system.

2.4.1 SYSTEMS OF CATEGORIZATION

There are several kinds of systems available for organizing water quality knowledge. Examples include

- Alphabetical
- Chemical Abstract System (CAS) number
- Chemical category such as organic, synthetic organic, inorganic, metal, etc.
- Class within a category such as alcohols, aldehydes, phthalates, etc.
- Regulatory lists, e.g., Safe Drinking Water Act Regulated Contaminants, Priority Pollutant List, etc.

Information concerning these contaminants was available in the EPA Register of Lists (USEPA, 1991; Miller, 1993). The Register of Lists (not available by web access in 2010) cross-referenced the chemicals with the statute listing and the EPA office administering. Such listing permitted cross-referencing in terms of CAS number, contaminant type (e.g., polycyclic aromatic hydrocarbon, amine, organic acid, particulate, etc.), empirical formula, contaminant classification (e.g., organic, synthetic organic, volatile organic, inorganic, metal), and the law or regulation under which the contaminant is regulated (e.g., Priority Pollutant List, CWA Section 304, CAA Section 112, RCRA, Sludge Regulations of February, 1993, SARA Section 313, SDWA).

2.4.2 ILLUSTRATIVE SYSTEM OF CONTAMINANT CATEGORIZATION

As noted, contaminants may be categorized by a variety of systems. Table 2.4 is another illustrative categorization of contaminants. The system shown was devised, for use here, to illustrate the broad scope of contaminant categories, the large number of contaminant species, and the idea that contaminant categorization may be devised to suit the purpose at hand (but is not done arbitrarily). Table 2.5 lists some of the many pathogenic organisms, showing the associated diseases, and is included to give some idea of the microbial hazards of untreated water. Figure 2.1 shows just three organisms that may be found in ambient waters; tens or hundreds of microorganism species are found commonly in a given sample of ambient water, depending on the source. Counts of an individual organism species could range from a few to several thousand.

TABLE 2.4
Contaminant Categorization

Category	Subcategory	Group	Representative Contaminants
Particle	Mineral	Clays	Montmorillonite Kaolinite
		Asbestos	Chrysotile Amphibole
	Biological	Viruses	Pathogenic (120 types of enteric viruses that cause disease; infectious hepatitis, poliomyelitis, coxsackie, and ECHO are common) Nonpathogenic
		Bacteria	Pathogenic Nonpathogenic
		Fungi	<i>Alternaria, Aspergillus, Cladosporium, Penicillium</i>
		Protozoa cysts	<i>Giardia lamblia</i> <i>Cryptosporidium parvum</i> <i>Entamoeba histolytica</i>
		Plankton	Diatoms Green algae Blue-green algae
		Invertebrates	Rotifers Nematodes Crustaceans Other arthropods Ciliates
		Microscopic materials	Plant debris Amorphous debris Pollen
	Inorganic	Cations	Mercury Lead Nickel Copper
		Anions	Chloride Sulfate Carbonate Bicarbonate
		Parameters	Nitrate Nitrite Alkalinity Calcium
			Hardness Ammonia ion Total dissolved solids (TDS) Specific electrical conductance (EC)
	Organic	Chlorinated hydrocarbons	Trihalomethane (THM) Chloroform Dichlorobromomethane Dibromochloromethane Bromoform Haloacetic acids (HAAs), chloropicrin Chloral hydrate Haloacetonitriles (HAN) Chloropropanes Haloketones Chlorophenols Aldehydes

(continued)

TABLE 2.4 (continued)
Contaminant Categorization

Category	Subcategory	Group	Representative Contaminants
		Surrogates	UV ₂₅₄ THMFP (24 h) THMFP (96 h)
		Total organic halides (TOX)	Trichlorophenol Chloroacetone Chloroethanol Chloroacetic acid
		Total organic carbon (TOC)	Trichlorophenol Chloroacetone Chloroethanol Chloroacetic acid
		Total organic carbon (TOC)	
		Natural organic matter (NOM)	
		Synthetic organic compounds	
		Aromatic compounds	Benzene
		Polycyclic aromatic hydrocarbons (PAH)	Alcohols Aldehydes
	Dissolved gases		Oxygen Nitrogen Carbon dioxide Ammonia Methane
	Characteristics		pH Temperature Color Taste Odor Floating material Esthetic
	Parameters		Specific electrical conductance (EC) Turbidity Particle counts

TABLE 2.5
Pathogenic Organisms

Category	Species	Disease
<i>120 types of enteric viruses cause disease</i>		
Enteroviruses ^a	Polioviruses (Sobsey, 1975, p. 415) (3)	Poliomyelitis, aseptic meningitis
	<i>Coxsackieviruses</i> A (Sobsey, 1975, p. 415) (23)	Herpangina, aseptic meningitis, exanthem
	<i>Coxsackieviruses</i> B (Sobsey, 1975, p. 415) (6)	Aseptic meningitis, epidemic myalgia, myocarditis, pericarditis
	<i>Echoviruses</i> (Sobsey, 1975, p. 415)	Aseptic meningitis, exanthem, gastroenteritis
Adenoviruses (Sobsey, 1975, p. 415) (31)		Upper respiratory illness, pharyngitis, conjunctivitis
Reoviruses (Sobsey, 1975, p. 415) (3)		Upper respiratory illness, diarrhea, exanthem
Hepatitis A viruses (Sobsey, 1975, p. 415)		Viral hepatitis type A or “infectious hepatitis”
Gastroenteritis viruses		Acute infectious nonbacterial gastroenteritis
	Coliphages	Infect coliform bacterium, <i>Escherichia coli</i>

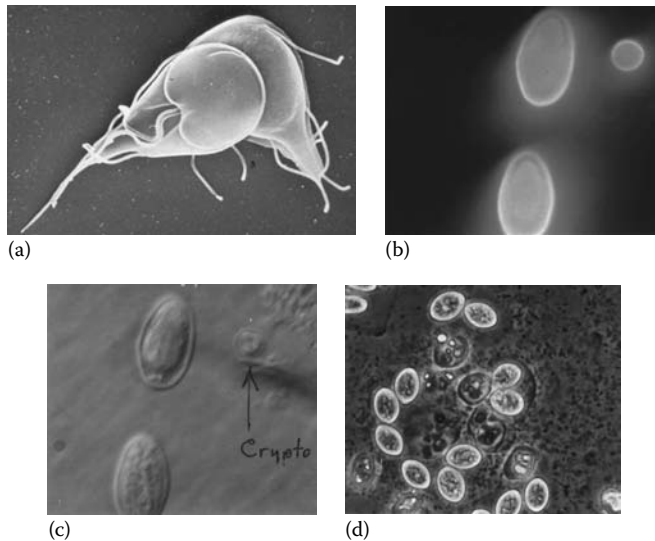


FIGURE 2.1 Examples of microorganisms found in water (the *Giardia* trophozoite is not found in water but occurs in the gut of a warm-blooded animal after excystation). (a) *Giardia* trophozoite, 10 μm width. (Courtesy of Dr. Judith L. Isaac-Renton, Public Health Laboratory Director and Professor, Medical Microbiology, The University of British Columbia, Vancouver, BC.) (b) *Giardia* cyst, 10 μm length, (c) *Cryptosporidium* oocyst, 5 μm width, (d) *Oocystis parva*, 400 \times . (Courtesy of Dr. Greg Sturbaum, CH Diagnostics and Consulting Services, Loveland, CO.)

2.5 UTILITY OF WATER QUALITY DATA

In water treatment, uses of water quality data include

1. Preliminary selection of unit processes: Source water quality must be characterized over the time period in which cyclical variation occurs (usually an annual cycle), and product water quality must be specified.
2. Process control: Requires water quality monitoring at selected node points in the treatment train in order to verify proper operation and to diagnose problems.
3. Regulatory compliance: Requires sampling of the effluent to document compliance with standards or criteria.
4. Monitoring of receiving waters: Confirms whether a stream standard has been violated.
5. Laboratory analyses: Data from the laboratories must be organized, understood, and utilized.
6. Data archiving: Data must be archived in a format suitable for long-term storage and retrieval.
7. Supervisory control and data acquisition (SCADA) systems.

Monitoring sensors report to computers for display and use in plant control. Pumps, valves, and motors are controlled.

2.5.1 CONTAMINANTS AND WATER USES

As stated, contaminants that may be found in water number in the thousands. The utility of water covers a wide variety of uses such as drinking water, industrial water, cooling water, esthetic appreciation, recreation contact, ecological habitats, irrigated agriculture, etc. Each of these categories of water use may be divided further. The objective of water quality criteria is to know the limits of each contaminant level that will not impair the uses intended. The scope of the undertaking may be depicted in a matrix of m uses in columns (perhaps several hundred columns would adequately depict the uses) and of n contaminants in rows (which may number several thousand). The number of possible interactions, i.e., criteria, are several thousand, with size, $m \cdot n$.

Since not all contaminants have a bearing on each use, the problem may be reduced considerably, but still there are hundreds or thousands of criteria that must be delineated. Examples of such criteria include (1) the electronics industry, where particle-free water is required; (2) boiler feed water for electric energy-generating plants, which must be “ion-free” water; (3) growing of citrus crops, where boron levels must be less than 0.5 mg/L, etc. These three examples indicate the nature of the criteria determination issue, e.g., that in-depth knowledge about the contaminant–use interaction must be generated. Most often, criteria are more complex than just a simple number, e.g., temperature affects how fish will survive under low dissolved oxygen conditions, the effect of TDS in irrigated agriculture depends on the plant species and the amount of water applied, etc.

2.6 COMBINATIONS OF QUALITY OF SOURCE WATERS AND PRODUCT WATERS

Source water quality and the required product water quality dictate the design and operation of a treatment train. Each source water is different, and standards for product water vary with the kind of use. Examples of uses include drinking water, discharge of municipal wastewaters to a receiving body, production of particle-free and molecule-free process water for microchip production, etc. The number of combinations is as large as the number of possible water sources times the number of possible water quality standards.

To the extent possible in water treatment where ambient water is used, the water of highest quality is sought as a source. Since high-quality sources have been mostly appropriated or are not available in some regions of countries, secondary sources have been committed to use to an increasingly greater extent. Thus, wastewaters are considered as sources of water, assuming the associated water rights to their use can be established. Also, as unit process technologies develop and expand, the number of treatment options increase, which may facilitate the use of lower-quality waters. The use of membranes, for example, has become increasingly more economical since about the mid-1990s, which has made feasible the use of even seawater as a source.

Table 2.6 indicates the variety of source waters and product water requirements. Other columns indicate examples of

TABLE 2.6
Combinations of Source Waters and Purposes of Treated Water as Contexts for Treatment

Source Water	Examples	Examples of Contaminants to Treat	Treatment	Product Water Purpose	Product Water Quality
Ambient, high-quality water such as streams and lakes	South Platte River in mountains	Turbidity levels <0.5 NTU Algae, rotifers, crustaceans TDS < 50 mg/L	Filtration		
Ambient water degraded by various treated point-source discharges and diffuse inputs	South Platte River below Denver	Turbidity levels <10 NTU NO ₃ ≈ 40–50 mg/L TDS ≈ 800 mg/L	Membranes		
Ambient water in the lower reaches of rivers degraded by natural hydrologic processes and waste discharges and agricultural runoff	Missouri River in the lower reaches, Mississippi River	Turbidity levels 20–200 NTU NO ₃ ⁻ ≈ 40–50 mg/L TDS ≈ 800 mg/L Hardness 200–300 mg/L			
Groundwater with surface water influence	South Platte alluvium below Denver, used as source water by several riparian communities	Turbidity levels <0.5 NTU NO ₃ ≈ 40–50 mg/L TDS ≈ 800 mg/L Hardness 200–300 mg/L			
Deep groundwater	Denver aquifer, some 300 m depth	Turbidity levels <0.5 NTU NO ₃ < 10 mg/L, TDS < 800 mg/L Hardness 200–300 mg/L Fe ²⁺ , Mn			
Municipal wastewater	Denver municipal sewage (with pretreated industrial wastes)	Suspended solids 300 mg/L BOD ≈ 300 mg/L Various pathogenic viruses, bacteria, cysts, worms			
Treated municipal wastewater	Denver Metro Wastewater Reclamation water effluent	Suspended solids 300 mg/L BOD ≈ 30 mg/L Possible low levels of pathogenic viruses, bacteria, cysts, worms			
	Water Factory 21	Viruses, carcinogens	Line softening Filtration Activated carbon Membranes (hyperfiltration)	Seawater barrier Municipal drinking water	Meets drinking water standards and other criteria—to be established

Treated municipal drinking water	Fort Collins drinking water	Particles TOC TDS	Filtration Activated carbon Membranes (hyperfiltration)	Electronics process water for chip manufacture Discharge to stream	Particle-free, TOC ≤ DL, TDS < DL
Industrial wastewater	Wastewaters from various industrial plants (steel fabrication, meat packing, metal plating, etc.)	Possible: heavy metals, high BOD	Pretreatment		
Industrial wastewater	Wastewaters from various industrial plants (steel fabrication, meat packing, metal plating, etc.)	Possible: heavy metals, toxic organics, high BOD		Discharge to municipal sewer	
Industrial wastewater pretreated	Effluent from HP discharged to municipal sewer	Reduced concentrations of specific contaminants and/or loading to municipal sewer			
Contaminated groundwater, contaminated soils	CERLA hazardous waste sites such as Rocky Mountain Arsenal	Possible: heavy metals, toxic organics (pesticides, herbicides, etc.)			
Source water	Examples	Examples of contaminants to treat	Treatment	Product water purpose	Product water quality
Groundwater not suitable for drinking water	Various groundwater basins such as found in the Intermountain West in the USA	Arsenic	Point of use (under sink or in basement or garage treatment) of ion-exchange or hyperfiltration membrane	Individual household drinking water	Controls on whether drinking water standards are met are not in place
Brackish water	San Francisco Bay	TDS ≈ 5000 mg/L	Membranes	Drinking water, industrial uses	
Seawater	Persian Gulf	TDS ≈ 35,000 mg/L	Multieffect evaporation distillation	Drinking water—blended with groundwater	Drinking water standards
Connate water	Oil field brines (near Bakersfield, CA)	TDS ≈ 38,000 mg/L	Oil removal	Reinjection into oil-bearing aquifer	Connate water with oil removed

source waters, typical contaminants treated, unit processes likely, and the purpose of the product water. As seen in Table 2.6, the variety of treatment situations includes treatment of high-quality surface waters for drinking water, treated municipal wastewater being further treated for agricultural use, industrial cooling water, injection to groundwater, or for drinking water, a contaminated groundwater being renovated by treatment and re-injected into an aquifer, etc. Each requires different criteria or standards and different treatment trains.

Table 2.6, column 3, indicates some of the contaminants to be reduced in concentration (the list is indicative only). Column 4 indicates typical unit processes.

In summary, the source water may be from any source and the product water may be whatever is required to meet the purpose of that water. Water quality must be characterized in each case. As a rule, criteria and standards govern the target of treatment.

PROBLEMS

2.1 Water Quality Profiles

State what you believe may be reasonable estimates for water quality profiles (constituents and concentrations and any important time variations) for several source waters that may be put to some use (for any purpose as listed in the second problem), such as

1. Mountain streams in the Rocky Mountains or in the High Sierras
2. Lower reaches of rivers such as the South Platte, the Missouri, the Ohio, the Sacramento, the Iowa, and the Cedar
3. Lakes such as Lake Superior, Lake Erie, and Lake Tahoe
4. Raw wastewaters to municipal treatment plants
5. Treated wastewaters from municipal treatment plants
6. Tertiary-treated wastewaters from municipal treatment plants
7. Raw wastewaters from industries such as electronics, metal plating, meat packing, brewery, poultry processing, electric energy generation, etc.

Develop case examples for situations that you select.

2.2 Water Quality Criteria

State what you believe may be reasonable expectations for water (constituents and concentrations and any important time variations) for purposes such as

1. Irrigation of citrus; vegetables such as lettuce, sugar beets, etc.
2. Farm uses such as livestock, poultry, etc.
3. Industries such as sugar beet refining, steel manufacturing, manufacture of electronic chips, electric energy generation, poultry processing, dairies, etc.
4. Drinking water such as in New York City, Seattle, Denver, New Orleans, Baghdad, Zurich, Milan, Istanbul, Palermo, etc.
5. Recreation such as swimming pools

6. Protection of saltwater environments such as the Mediterranean, the Caribbean, and the San Francisco Bay
7. Fisheries such as the Blue River near Dillon, Echo Lake in the High Sierras, Lake Michigan, the South Platte near Greeley, San Francisco Bay, the Ohio River, etc.

Develop case examples for situations that you select.

2.3 Source Water Quality and Treatment for Potable Water

Discuss some examples from the literature with respect to water quality profiles of source waters and the degree of treatment needed to meet certain uses that you may select. If you have access to records of treatment plants, then these provide firsthand references and are more “real-world.”

2.4 Water Quality Criteria/Standards

Look up criteria and standards for uses that you may select. Pick two categories of uses. Document your sources.

2.5 Organic Carbon over Annual Cycle

Discuss levels of TOC, and color, as they vary over an annual cycle in ambient waters that you may select.

2.6 Particles and Turbidity over Annual Cycle

Discuss levels of particles and turbidity as they vary over an annual cycle in ambient waters that you may select.

2.7 Water Quality Monitoring

Provide some examples of water quality monitoring with respect to

1. Regulatory surveillance
2. Process control
3. Database development

ACKNOWLEDGMENTS

Dr. Judith L. Isaac-Renton, director, Pathology and Laboratory of Medicine, The University of British Columbia, Vancouver, British Columbia, went through her files to locate a *Giardia* trophozoite electron-micrograph, shown in Figure 2.1a, and graciously provided permission for its use. Dr. Greg Sturbaum, president, CH Diagnostics and Consulting Services, Loveland, Colorado, gave permission to use Figures 2.1b,c,d, generated at CSU during the period 1993–1996.

APPENDIX 2.A: ORGANIC CARBON AS A CONTAMINANT

Each contaminant has its own unique story with respect to its occurrence in natural waters and in municipal and industrial discharges, effects on uses of various kinds, the nature and range of treatment for reduction in concentration, and regulatory requirements and their evolution. The story of organic carbon is reviewed here merely to illustrate the depth and

range of substantive content that may be extracted from the published material on a given contaminant. The organic carbon story (Box 2.A.1) is more extensive than most due to the health significance of carbonaceous DBPs in drinking water, which started to be understood only since the mid-1970s. In the United States, the subsequent regulations from EPA provided the mandates for the ensuing attention to DBPs. The review here is brief.

BOX 2.A.1 HUMIFICATION

Organic matter is comprised of humic and fulvic acids, indicating that their composition is of the same functional groups that make up lignins and, to a lesser extent, other plant polymers; they have more carboxylic acid functional groups, however, and they are surface active. The components of humus consist of plant polymer segments that have been oxidized to carboxylic acid groups at one or more ends of the segments. In the case of lignin polymers, the unaltered segments are more hydrophobic than the carboxylic groups. A molecule that has both a hydrophobic (nonpolar) part and a hydrophilic (polar) part is called an *amphiphile*.

Humification is a process by which biomass consisting of dead plant and animal remains is converted to humus; this is one of the basic steps of the carbon cycle. The organic compounds that make up plant and animal tissue are thermodynamically unstable in the oxidizing atmosphere of the earth's surface. The tissue is thus converted back to carbon dioxide and water that are catalyzed by enzymes from organisms. Some of the tissue is, however, only partially oxidized, which is the source of the organic compounds that accumulate as humus.

Vascular plants (those with water- and food-conducting tissues) are the dominant group in most terrestrial environments. The tissues of these plants consist of three groups of polymers: (1) cellulose, (2) hemicellulose, and (3) lignin. Lesser quantities of aliphatic polyesters, starches, proteins, phenolic macromolecular species, and lipids are present also.

The degradation of plant polymers involves depolymerization and oxidation reactions that are catalyzed by enzymes. Polysaccharide polymers such as cellulose and hemicellulose usually undergo hydrolytic depolymerization reactions, whereas lignin is degraded mainly by oxidation. Lipids undergo hydrolysis and oxidation. The products from lignin and lipid degradation are, in general, oxidized fragments in which much of the chemical structure of the original polymer is preserved.

In addition to amphiphiles produced by degradation, some of the lignin in wood is present as amphiphilic lignin-carbohydrate complexes. These complexes have number average molecular weights on the order of 6000–8000 Da.

According to Randtke (1988, p. 40), organic contaminants in water may be grouped into three classes:

1. *Natural organic matter* (NOM): Humic substances, microbial exudates, animal wastes, and products of degraded tissue
2. *Synthetic organic chemicals* (SOCs): Pesticides, volatile organic chemicals (VOCs), and other chemicals produced commercially or as waste products of manufacturing
3. *Chemical by-products and additives*: Substances that enter or are formed during treatment or in the distribution system

NOM is the source of color—a traditional contaminant, and is a precursor of DBPs, which are possible carcinogens, an issue since the mid-1970s. In addition, the residual NOM after treatment may serve as substrate for bacterial growths such as in the distribution system. In the United States, the issues of DBPs and SOC and possible health effects led to the 1974 Safe Drinking Water Act. Enforcement of the Act, by regulations, was stimulated by the capabilities to measure chemical concentrations in micrograms (μg) per liter through developments in instrumental analyses methods. In the case of organic compounds, such instrumental methods were exemplified by advances in gas chromatography and mass spectrography and associated lower costs (see Box 2.1).

2.A.1 CATEGORIES OF ORGANICS IN WATER

The organics found in waters are characterized according to various schemes, depending upon the water and the purpose of the characterization. The characterization evolves as new problems become known, and is a function of the purposes of the waters being considered. Wastewaters, for example, have been characterized traditionally in terms of BOD and SS. The BOD measurement is done by a 5 day BOD test and is dependent upon having a properly seeded test bottle. The test measures the organic carbon that is degraded in 5 days by the microbe's species in the seed. The test does not measure TOC, but for a given wastewater, BOD may be proportional to TOC. Only a portion of the organic carbon is biodegradable, and the test measures the portion that is biodegradable within a 5 day period. The test actually calculates BOD based on the measured concentration of dissolved oxygen at the beginning and end of the test under incubation at 20°C for 5 days, taking into account the dilution of the sample with "BOD" water. The BOD water contains a prescribed mixture of nutrients, as specified in *Standard Methods*, and is saturated with oxygen. This test has its origin most probably about 1900.

For natural waters that are sources of municipal water supplies, organic carbon was not of great concern until recent years, i.e., beginning about 1973. NOM occurs in surface waters in concentrations mostly in the range 3–6 mg/L, and as noted, is comprised mostly of humic and fulvic acids. These acids are products of decaying vegetative organic

matter that finds its way into ambient waters after rainfall, and of the decay of organic matter within a water body.

NOM causes the water to exhibit “color,” measured in terms of “standard color units” (SCU). Color, per se, has no health significance, but it does cause concern as it affects palatability of a drinking water. Since there is no health significance to color, it was assigned the status of a “secondary standard” in the 1973 Safe Drinking Water Act (PL93-523). Color has been considered as a parameter of drinking water quality since about the 1920s, and its reduction has been a traditional objective of water treatment (achieved by coagulation, and as measured by the “jar” test).

In the early 1970s, chlorinated organics were identified as carcinogens (Box 2.A.2) based on reports of higher levels of THMs in New Orleans drinking water, which precipitated the 1974 Safe Drinking Water Act (SDWA)—the first

BOX 2.A.2 DISINFECTION BY-PRODUCTS AS A NATIONAL ISSUE

A review of how disinfection by-products (DBPs) became a national issue was reviewed by James M. Symons (2001a,b), who, in the 1970s, was Chief of the Physical and Chemical Contaminants Removal Branch, Drinking Water Research Division, USEPA, Cincinnati. This position provided the vantage point of both perspective and responsibility to provide initiative.

Johannes Rook, a chemist with the Rotterdam Water Works, discovered chloroform in Rotterdam’s drinking water in 1971 while looking for sources of taste and odor, based on a “head-space” sampling/analysis technique he developed. Although he took special note of the chloroform as one among a score of micropollutants, there was not any special alarm, especially since the health officer mentioned that chloroform was a constituent of cough syrup and was not known as a toxin.

Also in 1971, Thomas Bellar, a chemist with EPA, was given an assignment to develop an adequate method to measure VOC contaminants in wastewater. The method developed was called by Bellar the “purge and trap” technique, which was an adjunct to gas chromatography. This was an analytical “breakthrough,” which opened the door for detecting and measuring organic contaminants at the $\mu\text{g/L}$ level. In measuring contaminants in samples of tap water, Bellar found chloroform but attributed the finding to laboratory contamination. In mid-1973, continuing to find chloroform, he decided to sample other drinking water sources. In sampling at several points in the water treatment train for the City of Cincinnati, he found that DBPs were related to the points of chlorination. For example, chloroform concentrations were (1) Ohio River, $0.9 \mu\text{g/L}$; (2) 80 min after chlorination and alum coagulation, $22.1 \mu\text{g/L}$; (3) 3 day settled water, $60.8 \mu\text{g/L}$; (4) treatment plant settled water following chlorination, $127 \mu\text{g/L}$; (5) filter effluent (after powdered

activated carbon and filtration), $83.9 \mu\text{g/L}$; and (6) finished water after a final chlorination, $94.0 \mu\text{g/L}$.

In early 1974, the EPA drinking water group pondered what to do about Bellar’s findings. Since the oral lethal dose was 120 mg/L , the issue seemed not an acute problem. In June 1974, however, an article in *Consumer Reports* reviewed the problem of organics in drinking water. The article was based partly on a 1972 report by USEPA and was to have strong influence on future events. The article was an indictment of the water quality of the Lower Mississippi River and stimulated public interest in the problem of organics in drinking water. James Symons returned to Europe in August 1974, and Rook described his theory that NOM, as measured by color, was a precursor to THM formation; his data showed a correlation between TTHM in $\mu\text{g/L}$ and color in Pt–Co units, and other possible precursors were eliminated by experiment and deduction. At that time, the structure of humic substances were not well defined. This meeting with Rook, and his evidence that color was a likely precursor to THMs, had a strong influence on Symons relative to the possible extent of the problem of THM’s in drinking water. Further stops in Europe, e.g., at the Swiss Federal Institute of Technology and at Karlsruhe, led to the decision at EPA that the THM issue was indeed important. Then, the National Organics Reconnaissance Survey was started to ascertain how widespread the problem of THMs was in the United States. Following this, in November 1974, the Environmental Defense Fund released an epidemiological study showing that disease rates for persons drinking New Orleans water were higher than those persons living in surrounding communities and drinking water from sources other than the Mississippi River. At the same time, a medical faculty member at the University of New Orleans stated that he had found halogen-substituted organic compounds in the blood of New Orleans residents. He also stated on national television that the water quality (i.e., with respect to chloroform) from the Mississippi River was of considerably better quality than the water produced by the water treatment plant. In December 1974, with an atmosphere that caused a lessening of public confidence in the drinking water industry, the Safe Drinking Water Act (PL93-523) was signed by President Ford.

The national publicity led to pointed criticisms of the drinking water industry. Further, many in the industry could not believe that the trace concentrations of chemicals could be hazardous to public health. (As an editorial aside, the THM issue and the later *Giardia* issue, which emerged in 1978, were combined stimuli that caused a major change in the culture of the U.S. water industry. The drinking water industry became energized and perhaps one might say the “glamour” field, which, during the 1960s, was in wastewater treatment.)

national legislation that would enforce nationwide drinking water standards. Consequently, pursuant to the 1973 SDWA, THM, one of the implicated species of chlorinated hydrocarbons, was regulated in 1978 with a MCL set at 100 $\mu\text{g/L}$. Subsequent research implicated the whole family of chlorinated hydrocarbons as being possibly carcinogenic, and also a variety of other organic compounds. Thus, in 1986, when the SDWA was reauthorized, the number of regulated contaminants in drinking water was expanded from 25 from the 1962 USPHS-recommended drinking water standards (Anon, 1962), to 83, with the requirement stipulated in the law that 25 new contaminants be added to the list every 3 years. The expanded list included natural organics, synthetic organics, and volatile organics. The change from recommended federal standards to mandated ones constituted a fundamental shift in the treatment of drinking water.

As the issue developed, the whole family of halogens, i.e., chlorine, bromine, and iodine, were implicated. The associated species of halogenated organic compounds, collectively, were termed TOX. Also, measures of THMs were developed. For example, by exposing a sample of organic carbon to chlorine for 24 h, measuring chlorine concentration before and after the test gives a measure called trihalomethane formation potential (THMFP-24 h). The same test extended for 96 h gives THMFP-96 h.

2.A.1.1 Color

Traditionally, dating back to perhaps 1915, the concern with organic matter was color, which was not pleasing esthetically. Other concerns were with its deleterious effects on industrial process waters, its chlorine demand, and interference with coagulation. The USPHS 1962 Drinking Water Standard set the limit as 15 color units on the platinum–cobalt scale, but the AWWA set ≤ 3 units as a goal for drinking water.

Regarding ambient waters, the color units for snowmelt mountain streams are low, e.g., <5 , but may rise to perhaps 50 units during spring runoff. By contrast, for swamp-like waters in the southeastern United States, color units may vary in the range 68–424. Examples of waters in this range include the Suwannee River at Fargo, Georgia; the Florida Everglades 20 miles northwest of Miami; and the Great Dismal Swamp near Norfolk, Virginia (Black and Christman, 1963).

2.A.1.2 Organic Carbon

An index of the organic content of water is TOC, which is a measure of all organic molecules in a water sample (i.e., those that are subject to being converted to carbon dioxide for measurement by infrared absorbance using a TOC analyzer). Figure 2.A.1 shows the ranges of TOC concentrations in seawater, groundwaters, surface waters, and raw and treated wastewaters.

More than 700 specific organic chemicals were identified in various drinking water sources in the United States in 1978 (FR43 (28):5759, Feb. 9, 1978). These compounds were from industrial and municipal discharges, urban and rural runoff, natural decomposition of vegetative and animal matter, and chlorination of water and wastewater.

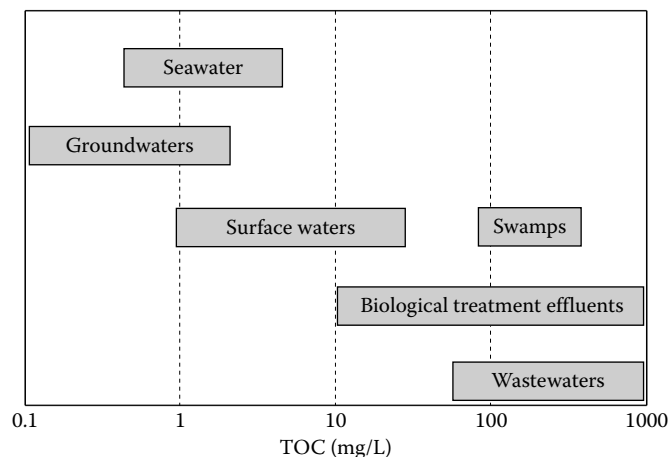


FIGURE 2.A.1 Ranges of TOC for a variety of waters.

At the time of the passage of the SDWA in December 1974, there were more than 12,000 chemical compounds known to be in commercial use, and many new compounds were being added to the list each year. These were called SOCs and included halogenated aliphatic and aromatic hydrocarbons such as carbon tetrachloride, dichloroethane, vinyl chloride, and chlorobenzenes; pesticides such as dieldrin and lindane; aromatics such as benzene, toluene, and styrene; polynuclear aromatics such as fluoranthene; nitrogenous compounds such as aniline and dinitrobenzene; esters such as dibutylphthalate; and many others.

2.A.1.3 UV₂₅₄

Since the mid-1980s, UV₂₅₄ absorbance has been accepted as a surrogate for TOC. Semmens and Field (1980, p. 477) used UV₂₆₀ (i.e., an ultraviolet light source at 260 nm wavelength), understanding the nature of the relationship. The use of UV converged on the 254 nm wavelength as the 1980s progressed, and was adopted by Hubel and Edzwald (1987) and others.

2.A.1.4 Synthetic Organic Carbon

Synthetic organic carbon compounds number in the tens of thousands and include pesticides and herbicides. This topic is mentioned to indicate its importance, but discussion is beyond the scope of this appendix.

2.A.2 DISINFECTION BY-PRODUCTS

The most abundant of the DBPs are from reactions with chlorine, with fewer from chloramines and chlorine dioxide, but with six from ozone. Chlorine has been the oxidant investigated most extensively. To illustrate a few structural formulae for some typical DBPs, Table 2.A.1 shows several representative groups. Each compound, i.e., each DBP, could be a part of any total organic halogen (TOX) measure.

Further insight as to the character of the organic carbon present in source waters is seen by the molecular weight

TABLE 2.A.1
Structural Formulae for Selected Disinfection By-Products

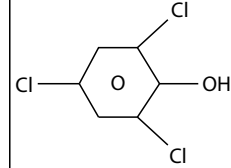
(a) Trihalomethanes			
$\begin{array}{c} \text{Cl} \\ | \\ \text{Cl}-\text{C}-\text{H} \\ | \\ \text{Cl} \end{array}$	$\begin{array}{c} \text{Cl} \\ | \\ \text{Cl}-\text{C}-\text{H} \\ | \\ \text{Br} \end{array}$	$\begin{array}{c} \text{Cl} \\ | \\ \text{Br}-\text{C}-\text{H} \\ | \\ \text{Br} \end{array}$	$\begin{array}{c} \text{Br} \\ | \\ \text{Br}-\text{C}-\text{H} \\ | \\ \text{Br} \end{array}$
Chloroform	Dichlorobromomethane	Dibromochloromethane	Bromoform

(b) Haloacetonitriles			
$\begin{array}{c} \text{Cl} \\ | \\ \text{Cl}-\text{C}-\text{C}\equiv\text{N} \\ | \\ \text{Cl} \end{array}$	$\begin{array}{c} \text{Cl} \\ | \\ \text{Cl}-\text{C}-\text{C}\equiv\text{N} \\ | \\ \text{H} \end{array}$	$\begin{array}{c} \text{Br} \\ | \\ \text{Cl}-\text{C}-\text{C}\equiv\text{N} \\ | \\ \text{H} \end{array}$	$\begin{array}{c} \text{Br} \\ | \\ \text{Br}-\text{C}-\text{C}\equiv\text{N} \\ | \\ \text{H} \end{array}$
Trichloroacetonitrile	Dichloroacetonitrile	Bromochloroacetonitrile	Dibromoacetonitrile

(c) Haloketones	
$\begin{array}{c} \text{Cl} \quad \text{O} \quad \text{H} \\ | \quad || \quad | \\ \text{Cl}-\text{C}-\text{C}-\text{C}-\text{N} \\ | \quad | \\ \text{H} \quad \text{H} \end{array}$	$\begin{array}{c} \text{Cl} \quad \text{O} \quad \text{H} \\ | \quad || \quad | \\ \text{Cl}-\text{C}-\text{C}-\text{C}-\text{N} \\ | \quad | \\ \text{Cl} \quad \text{H} \end{array}$
1,1-Dichloro-propanone	1,1,1-Trichloro-propanone

(d) Miscellaneous		
$\begin{array}{c} \text{Cl} \\ | \\ \text{Cl}-\text{C}-\text{NO}_2 \\ | \\ \text{Cl} \end{array}$	$\begin{array}{c} \text{Cl} \quad \text{H} \\ | \quad | \\ \text{Cl}-\text{C}-\text{C}-\text{OH} \\ | \quad | \\ \text{Cl} \quad \text{OH} \end{array}$	$\begin{array}{c} \text{Cl} \quad \text{H} \\ | \quad | \\ \text{Cl}-\text{C}-\text{C}-\text{OH} \\ | \quad | \\ \text{Cl} \quad \text{OH} \end{array}$
Chloroplorin	Chloral hydrate	Cyanogen chloride

(e) Haloacetic acids				
$\begin{array}{c} \text{Cl} \quad \text{O} \\ | \quad || \\ \text{H}-\text{C}-\text{C}-\text{OH} \\ | \\ \text{H} \end{array}$	$\begin{array}{c} \text{Cl} \quad \text{O} \\ | \quad || \\ \text{Cl}-\text{C}-\text{C}-\text{OH} \\ | \\ \text{N} \end{array}$	$\begin{array}{c} \text{Cl} \quad \text{O} \\ | \quad || \\ \text{Cl}-\text{C}-\text{C}-\text{OH} \\ | \\ \text{Cl} \end{array}$	$\begin{array}{c} \text{Cl} \quad \text{O} \\ | \quad || \\ \text{Cl}-\text{C}-\text{C}-\text{OH} \\ | \\ \text{Cl} \end{array}$	$\begin{array}{c} \text{Br} \quad \text{O} \\ | \quad || \\ \text{Br}-\text{C}-\text{C}-\text{OH} \\ | \\ \text{N} \end{array}$
Monochloroacetic acid	Dichloroacetic acid	Trichloroacetic acid	Monobromoacetic acid	Dibromoacetic acid

(f) Chlorophenols	(g) Aldehydes	
	$\begin{array}{c} \text{H} \\ | \\ \text{H}-\text{C}=\text{O} \end{array}$	$\begin{array}{c} \text{H} \quad \text{H} \\ | \quad | \\ \text{H}-\text{C}-\text{C}=\text{O} \\ | \\ \text{H} \end{array}$
2,4,6 Trichlorophenol	Formaldehyde	Acetaldehyde

Source: Krasner, S.W. et al., *J. Am. Water Works Assoc.*, 74(8), 41, August 1989.

TABLE 2.A.2

Chlorinated Species Detected by Contact between a Filtered Municipal Secondary Clarifier Effluent and 2000 mg/L Chlorine

Compound	Concentration (µg/L)	Compound	Concentration (µg/L)
Chloroform	—	Dichloromethoxytoluene	32
Dibromochloromethane	—	Trichloromethylstyrene (220)	10
Dichlorobutane	27	Trichloroethyl benzene (208)	12
3-Chloro-2-methylbut-1-ene	285	Dichloro-a-methyl benzyl alcohol (190)	10
Chlorocyclohexane (118)	20	Dichloro-bis(ethoxy)benzene (220)	30
Chloroalkyl acetate	—	Dichloro-a-methyl benzyl alcohol (190)	—
<i>o</i> -Dichlorobenzene	10	Trichloro- <i>N</i> -methylanisole	—
Tetrachloroacetone	11	Trichloro-a-methyl benzyl alcohol	25
<i>p</i> -Dichlorobenzene	10	Tetrachlorophenol	30
Chloroethylbenzene	21	Trichloro-a-methyl benzyl alcohol	50
Pentachloroacetone	30	Trichlorocumene (222)	—
Hexachloroacetone	30	Tetrachloroethylstyrene	—
Trichlorobenzene	—	Trichlorodimethoxybenzene (240)	—
Dichloroethyl benzene	20	Tetrachloromethoxytoluene (258)	40
Chlorocumene	—	Dichloroaniline derivative (205)	13
<i>N</i> -methyl-trichloroaniline	10	Dichloroaromatic derivative (249)	15
Dichlorotoluene	—	Dichloroacetate derivative (203)	20
Trichlorophenol	—	Trichlorophthalate derivative (296)	—
Chloro-a-methyl benzyl alcohol	—	Tetrachlorophthalate derivative (340)	—

Source: Glaze, W.H. and Henderson IV, J.E., *J. Water Pollut. Control Fed.*, 47(10), 2511, October 1975.

Notes: Parentheses indicates approximate molecular weights.

Sum of concentrations = 786 µg/L; estimated chlorinated organic compounds ≈3000–4000 mg/L.

distributions from a sample of water from the Mississippi River, given as 0–1,000, 48%; 1,000–25,000, 20%; 25,000–100,000, 13%; 100,000–1,000,000, 20%; >1,000,000, 2% (Tate and Fox, 1990, p. 104).

As to the reactions between chloramines and organic carbon, the TOX production is about the same as that resulting from chlorine (Johnson and Jensen, 1986). Further, the health effects of chloramines-treated water are nearly as severe as those of chlorine-treated water. Thus, while the chloramine solves the THM problem, it does not solve the health problem that the THM regulation was intended to address.

2.A.3 DISINFECTION BY-PRODUCTS IN SECONDARY EFFLUENTS

A question pertinent to wastewater treatment is the susceptibility of municipal wastewaters to the formation of DBPs. Such contaminants could constitute a hazard to aquatic life or a problem for downstream drinking water treatment plants. Glaze and Henderson (1975) investigated this issue by “super-chlorinating” (defined for their work as 2000 mg/L chlorine by gas injection, with 60 min contact time) the effluent from the secondary clarifiers at the Denton, Texas, wastewater treatment plant. For reference, 10 mg/L chlorine is a typical dosage of chlorine for wastewaters.

Their gas chromatograms showed over 100 peaks with more than 30 halogenated species detected, identified in

Table 2.A.2; most were aromatic derivatives. Some important points are (1) a host of chlorinated organic compounds form when a secondary effluent is subjected to chlorination, and (2) concentrations are in the µg/L range. These compounds formed also using a 10 mg/L chlorine dosage.

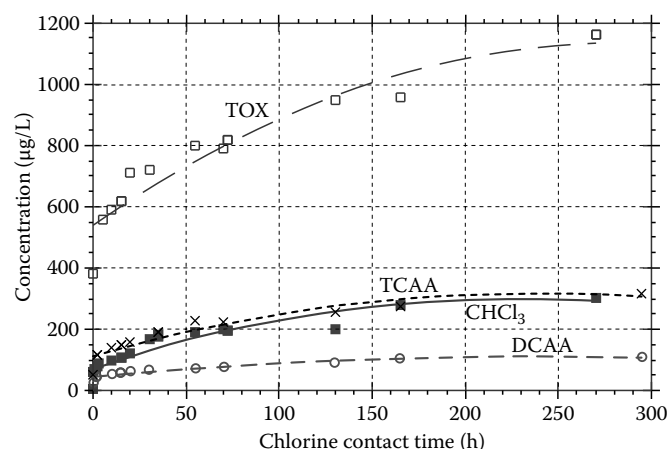


FIGURE 2.A.2 Chlorination by-products of Black Lake fulvic acid as affected by contact time at TOC 4.1 mg/L, pH 7.0, HOCl 20 mg/L. (Plotted from data of Reckhow, D.A. and Singer, P.C., *J. Am. Water Works Assoc.*, 76(4), 151, April 1984.)

2.A.4 DISINFECTANT SELECTION

Whenever disinfection occurs, oxidation also occurs. For a “safe” disinfection technology, (1) use a “safe” disinfectant and (2) remove the precursors to oxidation by-products before disinfecting (Trussell, 1992).

Regarding the distribution system, maintenance of a disinfectant residual is important. For factors to consider, include (1) residual stability, (2) residual toxicity, (3) effectiveness in biofilm control, and (4) Oxidation by-product issues (Trussell, 1992).

2.A.5 OTHER NOTES

The formation of chlorinated by-products increases with elapsed time. To illustrate, Figure 2.A.2 shows experimental data from chlorination of fulvic acids ($\text{HOCl} = 20 \text{ mg/L}$, $\text{pH} = 7.0$, $\text{TOC} = 4.1 \text{ mg/L}$) (Reckhow and Singer, 1984). The total halide concentration, TOX, was greater than 1100 $\mu\text{g/L}$ after 300 h, with about 600 $\mu\text{g/L}$ after 10 h. Also, as seen, the CHCl_3 , TCAA, and DCAA concentrations were significant fractions of the TOX concentration.

GLOSSARY

Aromatic compound: A class of molecules with six carbons and six hydrogens in a ring. A key property is their remarkable stability (Aihara, 1992, p. 62), which makes them valuable for many uses, e.g., paint thinner, mothball, gasoline additive, solvents, and as a source for synthetic fibers, resins, and dyes. The carbons are arranged in a closed hexagonal ring—a structure that does not want to react. The ring structure is the distinguishing aspect of the aromatic compounds. Ordinary combustion produces a wide variety of aromatic compounds. Ideally, when hydrocarbon fuels burn, they should form carbon dioxide and water; in reality, complete combustion is rare, and the soot and smoke contain a number of multiring or polycyclic, aromatic compounds, some of which are highly toxic.

Benzene: A ring compound with six carbons and six hydrogens, it is the prototype of a class of molecules known as the aromatic compounds.

Carcinogen: Substance that may cause the development of cancer after exposure at some threshold level or time duration.

Color: Substance in water that causes “color” as measured on the cobalt scale. Two kinds of color are “apparent” color and “true” color. The former is the result of a measurement using a sample of water “as is,” and the latter is the same measurement after filtering. Organic color is associated with natural organic matter.

Contaminant: (1) A substance in water other than molecular water. (2) A species added to another species that serves as a matrix. A few molecules of sodium chloride

added to a liter of water is a contaminant. (3) To make impure or corrupt by contact or mixture. A contaminant is a substance that is added to a pure substance.

Criterion: A standard, rule, or test on which a judgment or decision can be based.

Disinfection by-products (DBPs): The reactions of various disinfectants, e.g., chlorine, bromine, and ozone, with organic matter—natural organic matter in particular—result in a variety of by-products.

Disinfection by-product precursor: The reactions of various disinfectants, e.g., chlorine, bromine.

Dissolved organic carbon (DOC): Organic carbon passing a 0.45 μm filter (Edzwald, 1993, p. 24).

Fulvic acid: Similar to humic acids, except it is soluble at $\text{pH} = 1.0$ and believed to be in true solution vis-à-vis being colloidal (Randtke, 1988, p. 43). $\text{MW} < 5000$ and can be removed by GAC. Most DBPs are due to reactions with fulvic acid.

Geometric mean (n): *Mathematics* (1) The n th root, usually the positive n th root, of a product of n factors. Parkhurst (1998) states: The geometric mean is the antilog of the mean logarithm of a set of numbers or, equivalently, the n th root of the product of n numbers. State health departments use this term frequently in referring to concentrations of organisms.

Humic acids: High-MW negatively charged macromolecules having colloidal properties (Edzwald, 1993, p. 24). Also, they are insoluble at $\text{pH} = 2.0$ (Van Benschoten and Edzwald, 1990, p. 1527). $\text{MW} > 30,000$.

Humification: Humification is a process by which biomass consisting of dead plant and animal remains is converted to humis; this is one of the basic steps of the carbon cycle.

Log-normal distribution: The logarithms of the concentrations have a normal distribution. It is common statistical practice to transform such sample concentrations to logs before estimating confidence limits or performing statistical tests such as analysis of variance or t tests (Parkhurst, 1998). This term is found frequently in the literature.

Molality: Mass of a solute per unit mass of solvent, i.e., $\text{moles(solute)}/\text{moles(solvent)}$.

Molarity: Mass of a solute per unit volume of solvent, i.e., $\text{moles(solute)}/V(\text{solvent})$.

Mole fraction: In a given volume, the amount of a dissolved substance i in moles, i.e., n_i , divided by the summation of the moles of all substances in the solution, n ; i.e., mole fraction $i = n_i/n$.

Natural organic matter (NOM): The whole group of natural organic substances of which humic substances are a part.

Normative: Of, relating to, or prescribing a norm or standard: *normative* grammar. Related to the “norms” of a given culture.

NPT: Normal temperature and pressure, defined as 0°C and 101.325 kPa (1.00 atm), used mostly in European publications.

Palatable: (1) Acceptable to the taste (*American Heritage Dictionary*, 1996). (2) In potable water treatment, a drinking water palatability is measured in terms of taste, odor, color, and turbidity.

Particulate organic carbon (POC): Organic carbon passing retained by a 0.45 μm filter. Usually, POC is a small fraction of the TOC compared to DOC and includes bacteria, algae, zooplankton, and organic detritus (Edzwald, 1993, p. 24).

Pollutant: (1) A contaminant level that interferes with, or is perceived to interfere with, a particular use of water. (2) (*n.*) Something that pollutes, especially a waste material that contaminates air, soil, or water. (3) (*n.*) Something that pollutes, especially a harmful chemical or waste material discharged into the water or atmosphere.

Potable: Fit to drink (*American Heritage Dictionary*, 1996).

Specific: A physical quantity divided by its mass; examples include specific heat capacity, specific weight (from Elias, 1997, p. 444).

Standard: An acknowledged measure of comparison for quantitative or qualitative value; a criterion.

State: The “state” of a parcel of water is defined by its physical and chemical characteristics. In physical chemistry, pressure, temperature, and volume are “state” parameters. In a more general sense as applied to unit processes, we would include concentrations of particles and dissolved molecules and ions.

STP: Standard temperature and pressure defined as 20°C and 101.325 kPa (1.00 atm).

Surrogate: A substitute; a quantity that takes the place of another.

Total organic carbon (TOC): All carbon in water when measured by a total organic carbon analyzer is converted to carbon dioxide gas. The carbon dioxide gas is then measured by an infrared wavelength absorbance, calibrated in terms of mg C/L.

TOX: Total organic halides. The principal halides are chlorine, bromine, and iodine (fluorine is also a halogen). If any of these elements react with any organic compound, the product may be termed an organic halide. Thus, the multitude of halogenated organic compounds may be represented collectively by a single parameter, TOX, in lieu of trying to identify each species present and the respective concentrations.

Trihalomethane formation potential (THMFP): The results of a test in which a given water sample is exposed to a known concentration of chlorine and permitted to react over a given time duration, e.g., 24 or 96 h. The loss of chlorine is a measure of THMFP.

Utility: The quality or condition of being useful; usefulness.

UV₂₅₄: Ultraviolet light wavelength, which refers to absorbance of the 254 nm wavelength by a water sample in a standard cuvette. The 254 nm wavelength has been accepted as a surrogate for TOC.

Water quality: The “state” of a given water volume in terms of concentrations of suspended and dissolved substances and of any other state measures, including temperature and pH.

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3 Models

In education, especially at the undergraduate level, we emphasize problems in which the parameters are well defined. In practice, however, this is not the reality. Knowledge may be incomplete: data on inputs may be lacking, methods of solution may not be well delineated, and even the objectives may be nebulous. All of this is contrary to the common perception of engineering, i.e., that it is deterministic and largely a matter of computation.

This chapter examines some of the approaches for attacking problems. The concept of modeling is a theme common to all. Modeling is an engineering method (Box 3.1).

3.1 UNIT PROCESSES

About 10–15 unit processes comprise the field of water treatment, depending on how they are categorized. Perhaps there are 80–100 technologies developed from them. Table 3.1 lists 13 unit processes and associated technologies. Fundamental principles operative include

- Sieving of particles by screens (ranging from bacteria by membranes to large objects by bar screens)
- Creating conditions for application of a “passive” force on particles (e.g., gravity), or an “active” force (e.g., centrifugal) to cause transport
- Turbulence and diffusion for the transport of particles to cause contacts between reactants
- Charge neutralization
- van der Waals attraction between molecules and a surface (such as activated carbon), or charge attraction (such as between ions and an ion-exchanger material)
- Various chemical reactions such as
 - Redox, acid–base
 - Precipitation
 - Complexation
 - Biochemical
 - Cell synthesis
- Membrane processes involving retention of ions and molecules, i.e., reverse osmosis/nanofiltration

Generally, the unit processes listed in Table 3.1 are the results from a heritage of only since about 1900, albeit the earliest technology was slow sand, with the first installation in 1829 for London. Proprietary innovations have expanded the array of technologies, but most are variations of the unit processes listed in Table 3.1.

3.2 MODELS

A model is a means to represent a portion of a reality. The model is “valid” if the points of the model predict accurately the corresponding points of the system being modeled. As a rule, the system being modeled, i.e., the “prototype,” is a full-scale process. Examples include an activated sludge reactor, a biofilm reactor, a plate settler, a slow sand filter, a rapid rate filtration system, a granular activated carbon reactor, an ozone reactor, etc. Natural systems may be modeled also, e.g., water quality of streams and lakes, groundwater, etc., with mathematical models being a primary method of determining the effects of pollutant discharges on such systems.

Table 3.2 lists various forms of models and describes their respective characteristics and positive and negative attributes. The notion of what may comprise a model, Table 3.2, illustrates that a wide range of forms may be encompassed. Thus, a model may include lore, judgment, description, bench testing, pilot plants, demonstration plants, and mathematical models.

3.2.1 CATEGORIES OF MODELS

A model is a means to “represent.” Thus, a photograph is a model, along with language, a drawing, a painting, a map, a plot, an equation, an array of 0 and 1 digits stored in a computer, or any kind of representation. To be an engineering model, this is necessary but not sufficient. An engineering model, we might assert, must also have utility in projecting from the unknown to the known.

More commonly in engineering, we think of a model in terms of a pilot plant or as a set of coordinated equations in a computer algorithm or in a spreadsheet or even a single equation. Table 3.2 lists some of the more common things that we do in engineering that are really “forms” of models. They qualify as meeting the requirements of a “model,” as defined here. Indeed, the various model forms comprise engineering practice, e.g., lore, judgment, extrapolation, bench scale testing, pilot plants, demonstration plants, and mathematical modeling. As an additional note, each model form in Table 3.2 may be thought of as a “black box.” In other words, a model as a “black box” accepts a set of “inputs,” without regard to how it works, and generates outputs.

3.2.2 THE BLACK BOX

The proverbial “black box” has its place as a primary engineering method. Figure 3.1 depicts the concept of the black

BOX 3.1 PHILOSOPHY OF MODELING

Modeling has two themes of logic: inductive and deductive, formalized by Sir Francis Bacon (1561–1626) and René Descartes (1596–1650), respectively. Bacon extolled observation and practical outcomes, while Descartes believed that pure reasoning was the basis for problem solving (Durant, 1926).

The essence of empiricism is observation. Engineering forms include bench scale testing, pilot plants, demonstration plants, evaluations of existing plants, etc. Also included in this category are judgment, lore, and “black box” approaches. Rational models include equations based on a premise leading to an understanding of process mechanisms. Mathematical modeling, scenarios, animations, etc., are modern outcomes. Most problem solving is a blend of empiricism and rationality rather than being exclusively one or the other.

The organization and displays of solutions are important also, as the amount of data generated by physical models or computer models may be overwhelming. Spreadsheets and plots provide a means to organize and present results such that a wide range of conditions can be communicated easily and clearly. Computer animations provide a means to display succinctly and to grasp more easily complex results that could be otherwise difficult to assimilate.

All of these various kinds of models have roles in engineering problem solving. Even when we know little about a problem, some form of model provides a means to identify variables, organize data, test assumptions, generate plausible solutions, and communicate results.

box, illustrating the idea of how the values of dependent variables are generated by maintaining y and z constant while varying x ; ϕ and ψ are measured for each level of x at fixed values of y and z . Then y is changed to a new value, and the process is repeated. After all the values of y are explored, z may be changed to a new level, and the foregoing is repeated for each value of z that is to be explored. Suppose that there are 5 levels of x , 8 of y , and 10 of z . Then the number of experiments would be $5 \times 8 \times 10 = 400$. In exploring a hypothetical “surface,” a substantial amount of effort is required. An example of the foregoing in more concrete terms is the traditional jar test. Thousands of experiments may be done where a treatment process is being explored, i.e., to determine coagulant dosage, x , and polymer dosage, y , for several seasonal water quality conditions, z .

The “black box” is a device to generate outputs (dependent variables— ϕ and ψ) from selected inputs (independent variables— x , y , z), which may define a useful portion of a functional relationship. Virtually any means to generate outputs from inputs can be considered a “black box.” Such means could include judgment, physical models, and mathematical models.

3.2.2.1 Plots

The kind of experimental program outlined above might be called “parametric exploration.” Figure 3.2 illustrates the output of ϕ as a function of x and y , with z constant, i.e., $\phi v \cdot x$ for $y = y_1, y_2, \dots, y_n$ and $z = z_1$, where z represents a set of conditions that are maintained constant during the testing. To be more specific, the system being modeled is a rotating drum microscreen. The flow of water through the screen divided by its submerged area is the velocity of water through the screen, v , which is the “dependent” variable, i.e., ϕ . Then v is affected by the independent variables, headloss, h , across the screen, as seen by the curve and the rotational velocity, ω , of the drum, in which h and ω correspond to x and y , respectively. The set of curves of Figure 3.2 is for all other conditions being maintained constant. If, for example, the suspension changes (such as one species of algae instead of another) or the screen size changes, then another set of conditions exists and another set of curves must be generated. Thus, a set of one or more plots, such as seen in Figure 3.2, is the end result of a black box experimental program.

3.2.3 PHYSICAL MODELS

A physical model is a smaller-scale setup of equipment intended to replicate the process being considered. One appeal of a physical model is that variables not anticipated are included passively. The outputs, i.e., dependent variables, thus reflect all independent variables, not just the ones identified.

With the smaller scale, the model is cheaper and easier to operate than a full-scale system. Further, the independent variables can be controlled so that the influence of each on the dependent variables can be investigated. Physical models include bench scale testing, pilot plants, and demonstration scale plants.

3.2.3.1 Bench Scale Testing

Bench scale testing may include jar tests to determine chemical dosages, kinetic coefficients, isotherm constants, and generating relationships between various other kinds of intensive variables. The testing is “one dimensional” in nature, i.e., the intent is to examine the influences of only one or two independent variables (such as screen size) in selected dependent variables (such as effluent concentration).

3.2.3.2 Pilot Plants

One purpose of a pilot plant is to generate functional relationships between dependent and independent variables. The extent to which this is done, i.e., the scope of the experimental program, depends upon the nature of the problem and the budget available.

Another purpose of a pilot plant study may be to determine coefficients of a mathematical model. A mathematical model has greater utility than a set of plots.

Pilot plant experiments will yield, almost without exception, unexpected results that lead to new insights and serendipitous findings. Thus, any plan devised in anticipation of a set of results should have flexibility to incorporate new findings.

TABLE 3.1
Unit Processes and Technologies in Water Treatment

Unit Process	Principle	Technology
1. Screening	Sieving	Bar screens Coarse screening Microscreening
2. Sedimentation	Gravity force	Plain sedimentation Flocculant settling Flotation Oil separation Grit chambers Aerated grit chambers
3. Coagulation	Charge neutralization	Rapid mix/coagulants
4. Flocculation	Turbulence	Paddle wheels Baffles
5. Chemical precipitation	Equilibrium concentration is exceeded	Softening Phosphate removal Heavy metal removal
6. Filtration	Adsorption on biofilm Adsorption between charge-neutralized particle and collector	Slow sand Rapid rate
7. Membrane processes	Sieving of micron-size particles Sieving of macromolecules Retention of organic molecules Retention of ions	Microfiltration Ultrafiltration Nanofiltration Hyperfiltration
8. Adsorption	van der Waals attraction Electrostatic attraction	Powdered activated carbon Granular activated carbon Ion exchange Activated alumina
9. Oxidation	Creating conditions for negative free energy of reaction	Ozone Chlorine dioxide Supercritical Wet air Chemical oxidation
10. Gas transfer	Diffusion transport	Oxygen transfer Air stripping
11. Biological aerobic treatment	Microbial growth	Activated sludge Fixed film reactors
12. Biological anaerobic treatment	Microbial growth	Digestors Lagoons
13. Disinfection	Oxidation	Chlorine Ozone UV

3.2.3.3 Demonstration Plants

A demonstration plant is similar to a pilot plant but is larger in scale. The scale is too large, as a rule, to generate economically the functional relationships between dependent and independent variables. There are many variables that may be difficult to control, e.g., temperature, influent concentration, etc. At the same time, the fact that the demonstration plant operates continuously means that the processes must handle the variations in input variables and exigencies that exist in the “real world.” An example may be with the liner used

for the steel tanks that define the volume of an activated carbon reactor, which may be acrylic or PVC in a pilot plant. Steel is subject to corrosion, and so a liner (e.g., rubber or fiberglass) is used, which is subject to pinholes or cracks. Many problems of this nature are not identified before the plant is constructed, and so the demonstration scale permits both problem identification and evaluation.

Ostensibly, the demonstration plant should be a “capstone” study for a contemplated full-scale plant. A demonstration plant, however, is large enough to ascertain the impacts of

TABLE 3.2
Forms of Models and Their Characteristics

Model Form	Characteristics	Positive	Negative
Lore	Rules, methods passed by tradition; rationale not necessary	Provides a result that fits with past Familiar	Validity accepted by faith
Judgment	Education and experience, coupled with intuition, provide a basis for decisions	Common A necessary adjunct to any modeling Sometimes the only alternative	Accuracy limited Requires experience
Descriptive	Measurements, impressions, images, etc. used as a basis for transfer to a new design	Inexpensive Based on actual experience	Qualitative
Extrapolation	Projection from measured data to new design	Necessary adjunct to any modeling Inexpensive Based on actual experience Can evaluate coefficients of mathematical models	Validity is subjective Independent variables not controlled Variables not identified may be influential Accuracy limited
Bench testing	Variables isolated to a few and would involve limited kinds of relationships; small in scale	Independent variables can be controlled High accuracy likely	Limited to specific measures
Pilot plant	Complex systems can be simulated with variables controlled	Can maintain constant selected independent variables Can explore the effects of selected independent variables Can develop empirical models Can evaluate coefficients of mathematical models	Requires separate project Generally expensive
Demonstration plant	Emphasis is on maintenance, costs, logistics, operation difficulties	Looks beyond process design to ascertain the roles of dependent variables such as maintenance, costs, logistics, etc.	Expensive and requires time commitment of several years
Mathematical	Independent variables are linked to dependent variables by mathematical relationships	Requires understanding of relationships Experiments can be conducted to explore effects of selected independent variables Complex systems can be evaluated	Expensive to develop coefficients Coefficients may be lacking or inaccurate Validity must be ascertained.
Criteria	Limits are defined by experience, physical modeling, tradition	Simple to apply	May be simplistic, i.e., some key considerations are not included

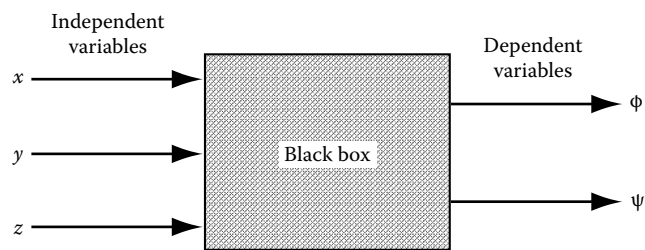


FIGURE 3.1 Black box. x varies, y and z held constant; are measured ϕ and ψ .

operation variables such as storage volumes for chemicals, costs of chemicals, energy, labor, maintenance, etc. In addition, the reliability of the plant can be assessed prior to full scale. Public relations may be another aspect of the demonstration. Examples include the Denver Potable Water Reuse Plant and Water Factory 21 in Orange County, California. These plants have been highly visible and prominent facilities evoking a great deal of public interest as well as political support.

3.2.4 MATHEMATICAL MODELS

A mathematical model epitomizes the deductive approach. The mathematical model starts with a premise. From the premise, we build an “edifice,” i.e., the mathematical model. If the premise is not valid, neither is the model.

A system is represented by mathematical relationships that relate dependent variables to independent variables. Usually coefficients or constants are a part of the equations (see Example 5.3).

3.2.5 COMPUTER MODELS

A computer model is sometimes an extension of a mathematical model, but not necessarily. As an extension of a mathematical model, the computer model may represent a “complex” system depicted by equations, with outputs from one unit comprising inputs to another. The computer model in such a case is a means for “bookkeeping” as variables change in space and time. The steps in organizing the computational scheme are called an “algorithm.”