大学环境教育丛书

影印版

Metcalf & Eddy, Inc.

Wastewater Engineering

Treatment and Reuse

(Fourth Edition)

废水工程

处理与回用

（第4版）

II

Mc Graw Hill

清华大学出版社

大 学 环 境 教 育 丛 书

（影印版）

Metcalf & Eddy, Inc.

Wastewater Engineering

Treatment and Reuse

(Fourth Edition)

废水工程

处理与回用

（第4版）

— II —

George Tchobanoglous
Franklin L. Burton
H. David Stensel

修订

清华大学出版社

(京)新登字 158 号

Wastewater Engineering: Treatment and Reuse(Fourth Edition)

废水工程：处理与回用(第 4 版)

Metcalf & Eddy Inc.

EISBN 0-07-112250-8

北京市版权局著作权合同登记号：图字：01-2002-4627

书　名：废水工程：处理与回用(第 4 版)Ⅱ
作　者：Metcalf & Eddy, Inc.
出版者：清华大学出版社(北京清华大学学研大厦,邮编 100084)
　　http://www.tup.tsinghua.edu.cn
印刷者：世界知识印刷厂
发行者：新华书店总店北京发行所
开　本：787×960 1/16　印张：43.75
版　次：2003 年 1 月第 1 版　2003 年 1 月第 1 次印刷
书　号：ISBN 7-302-05857-1/X・42
印　数：0001～3000
定　价：169.00 元(全 3 册总定价)

出版前言

在跨入21世纪之际，面临不断恶化的生存环境，人类清醒地认识到要走可持续发展之路。而发展环境教育是解决环境问题和实施可持续发展战略的根本。高等学校的环境教育，是提高新世纪建设者的环境意识，并向社会输送环境保护专门人才的重要途径。为了反映国外环境类教材的最新内容和编写风格，同时也为了提高学生阅读专业文献和获取信息的能力，我们精选了一些国外优秀的环境类教材，组成大学环境教育丛书（影印版），本书即为其中的一册。所选教材均在国外被广泛采用，多数已再版，书中不仅介绍了有关概念、原理及技术方法，给出了丰富的数据，还反映了作者不同的学术观点。

我们希望这套丛书能对高等院校师生和广大科技人员有所帮助，同时对我国环境教育的发展作出贡献。

清华大学出版社

2002年8月

About the Authors

George Tchobanoglous is a professor emeritus of environmental engineering in the Department of Civil and Environmental Engineering at the University of California at Davis. He received a B.S. degree in civil engineering from the University of the Pacific, an M.S. degree in sanitary engineering from the University of California at Berkeley, and a Ph.D. in environmental engineering from Stanford University. His principal research interests are in the areas of wastewater treatment, wastewater filtration, UV disinfection, aquatic wastewater management systems, solid waste management, and wastewater management for small systems. He has authored or coauthored over 350 technical publications, including 12 textbooks and two reference works. The textbooks are used in more than 200 colleges and universities throughout the United States. The textbooks and reference books are also used extensively by practicing engineers both in the United States and abroad. Professor Tchobanoglous serves nationally and internationally as consultant to both governmental agencies and private concerns. An active member of numerous professional societies, he is a past president of the Association of Environmental Engineering and Science Professors. He is a registered civil engineer in California.

Franklin L. Burton spent 30 years with Metcalf & Eddy serving as vice president and chief engineer in their western regional office in Palo Alto, CA. He received a B.S. degree in mechanical engineering from Lehigh University and an M.S. degree in civil engineering from the University of Michigan. He has been involved in the planning, design, and technical review of over 50 wastewater treatment plants. He was the coauthor of the third edition of this textbook. He retired from Metcalf & Eddy in 1986 and is in private practice in Los Altos, CA, specializing in treatment technology evaluation, energy management, facilities design review, and value engineering. He is a registered civil and mechanical engineer in California and is a life member of the American Society of Civil Engineers, Water Environment Federation, and the American Water Works Association.

H. David Stensel is a professor of civil and environmental engineering at the University of Washington, Seattle, WA. Prior to his academic positions, he spent 10 years in practice developing and applying industrial and municipal wastewater treatment processes. He received a B.S. degree in civil engineering from Union College, Schenectady, NY, and M.E. and Ph.D. degrees in environmental engineering from Cornell University. His principal research interests are in the areas of wastewater treatment, biological nutrient removal, sludge processing methods, biodegradation of hazardous substances, and stormwater treatment. He has authored or coauthored over 100 technical publications and a textbook on biological nutrient removal. He has received the ASCE Rudolf Hering Medal and twice received the Water Environment Federation Harrison

Prescott Eddy Medal for his research contributions. He is a member of numerous professional societies, and has served as chair of the ASCE Environmental Engineering Division, treasurer of the American Association of Environmental Engineering Professors, and associate editor of the *Water Environment Federation Research Journal.* He is a registered professional engineer and a diplomate in the American Academy of Environmental Engineers.

Preface

During the past 12 years since the publication of the third edition of this textbook, the number of new developments and changes that have occurred in the field of wastewater engineering has been dramatic, especially with respect to

(1) the characterization of the constituents found in wastewater, both in terms of the range of constituents and the detection limits;
(2) a greater fundamental understanding of the mechanisms of biological wastewater treatment;
(3) the application of advanced treatment methods for the removal of specific constituents;
(4) the increased emphasis on the management of the biosolids resulting from the treatment of wastewater; and
(5) the issuance of more comprehensive and restrictive permit requirements for the discharge and reuse of treated wastewater.

The fourth edition of this textbook has been prepared to address the significant new developments and changes that have occurred in the field and to correct other issues with the third edition to make the fourth edition more user friendly. For example, the theory and practice chapters, separated in the third edition, are now combined in the fourth edition to provide subject continuity and eliminate redundancy. Because of the importance of biological wastewater treatment, four separate chapters have been devoted to this subject. The chapter on advanced wastewater treatment has been expanded to include processes that are increasingly required to meet more stringent discharge requirements. A new chapter on disinfection has been added to deal with recent developments in the field. The chapter on reclamation and reuse has been revised completely and much new material has been added. Because of the importance of biosolids management, an entire chapter is devoted to this subject. The issues of process design and performance to meet more stringent permit requirements, including the upgrading of existing treatment plants, are considered in Chapter 15.

IMPORTANT FEATURES OF THIS BOOK

Following the practice in the third edition, more than 100 new example problems have been worked out in detail to enhance the readers' understanding of the basic concepts presented in the text. Wherever possible, spreadsheet solutions are presented. To aid in the planning, analysis, and design of wastewater management systems, design data and information are summarized and presented in more than 300 tables, most of which are new. To illustrate the principles and facilities involved in the field of wastewater management, over 570 illustrations, graphs, diagrams, and photographs are included. To help the readers of this textbook hone their analytical skills and mastery of the material,

problems and discussion topics are included at the end of each chapter. Selected references are also provided for each chapter.

The International System (SI) of Units is used in the fourth edition. The use of SI units is consistent with teaching practice in most U.S. universities and in many countries throughout the world. In general, dual sets of units (i.e., SI and U.S. customary) have been used for the data tables. Where the use of double units was not possible, conversion factors are included as a footnote to the table.

To further increase the utility of this textbook, several appendixes have been included. Conversion factors from International System (SI) of Units to U.S. Customary Units and the reverse are presented in Appendixes A–1 and A–2, respectively. Conversion factors commonly used for the analysis and design of wastewater management systems are presented in Appendix A–3. Abbreviations for SI and U.S. Customary units are presented in Appendixes A–4 and A–5, respectively. Physical characteristics of air and selected gases and water are presented in Appendixes B and C, respectively. Dissolved oxygen concentrations in water as a function of temperature are presented in Appendix D. Tables of most probable numbers (MPN) are presented in Appendix E, carbonate equilibrium is considered in Appendix F, and Moody diagrams for the analysis of flow in pipes are presented in Appendix G.

USE OF THIS BOOK

Enough material is presented in this textbook to support a variety of courses for one or two semesters or three quarters at either the undergraduate or graduate level. The specific topics to be covered will depend on the time available and the course objectives. Suggested course outlines follow.

For a one-semester introductory course on wastewater treatment, the following material is suggested:

Topic	Chapter	Sections
Introduction to wastewater treatment	1	All
Wastewater characteristics	2	All
Wastewater flowrates and constituent loadings	3	All
Introduction to process analysis	4	All
Physical unit operations	5	5–1 to 5–8
Chemical unit operations	6	6–1, 6–2,
Introduction to biological treatment of wastewater	7	All
Disinfection	12	12–1 to 12–5, 12–9
Water reuse	13	13–1 to 13–2
Biosolids management	14	All
Introduction to treatment plant performance	15	15–1 to 15–3

For a two-semester course on wastewater treatment, the following material is suggested:

Topic	Chapter	Sections
Introduction to wastewater treatment	1	All
Wastewater characteristics	2	All
Wastewater flowrates and constituent loadings	3	All
Introduction to process analysis	4	All
Introduction to treatment plant performance	15	15–1 to 15–3
Physical unit operations	5	All
Chemical unit operations	6	All
Introduction to biological treatment of wastewater	7	All
Suspended growth biological treatment processes	8	All
Attached growth and combined biological treatment processes	9	9–1 to 9–5
Anaerobic suspended and attached growth treatment processes	10	10–1, 10–2, 10–4
Disinfection	12	All
Water reuse	13	All
Biosolids management	14	All
Process control and upgrading treatment plant performance	15	15–3 to 15–7

For a one-semester course on biological wastewater treatment, the following material is suggested:

Topic	Chapter	Sections
Introduction to wastewater treatment	1	All
Wastewater characteristics	2	All
Introduction to process analysis	4	All
Introduction to treatment plant performance	15	15–1 to 15–3
Introduction to biological treatment of wastewater	7	All
Suspended growth biological treatment processes	8	All
Attached growth and combined biological treatment processes	9	All
Anaerobic suspended and attached growth treatment processes	10	All
Anaerobic and aerobic digestion and composting	14	14–9 to 14–11

For a one-semester course on wastewater reclamation and reuse, the following material is suggested:

Topic	Chapter	Sections
Introduction to wastewater treatment	1	All
Wastewater characteristics	2	All
Introduction to water reclamation and reuse	13	13–1
Introduction to risk assessment	13	13–3
Introduction to treatment plant performance	15	15–1 to 15–3
Advanced wastewater treatment (optional)	11	11–6
Disinfection	12	12–1 to 12–5, 12–7 to 12–9
Water reclamation technologies	13	13–4
Storage of reclaimed water	13	13–5
Reuse of reclaimed water	13	13–6 to 13–9
Planning consideration for reclamation and reuse	13	10

For a one-semester course on physical and chemical unit operations and processes, the following material is suggested. It should be noted that material listed below could be supplemented with additional examples from water treatment.

Topic	Chapter	Sections
Introduction to process analysis	4, 15	All
Introduction to treatment plant performance	15	15–1 to 15–3
Introduction to physical unit operations		
Mixing and flocculation	5	5–4
Sedimentation	5	5–5, 5–7, 5–8
Gas transfer	5	5–11 to 5–12
Filtration (conventional depth filtration)	11	11–3, 11–4
Membrane filtration	11	11–6
Adsorption	11	11–7
Gas stripping	5, 11	5–13, 11–8
UV disinfection	12	12–9
Introduction to chemical unit processes		6–2
Coagulation	6	6–2
Chemical precipitation	6	6–3 to 6–5
Ion exchange	11	11–9
Water stabilization	6	6–7
Chemical oxidation (conventional)	6	6–6
Advanced oxidation processes	11	11–9

ACKNOWLEDGMENTS

A book of this magnitude could not have been written without the assistance of numerous individuals. First and foremost, Mr. Harold Leverenz, a doctoral candidate at the University of California at Davis, provided exceptional assistance. He read and commented on all of the drafts, checked the problems, and prepared many of the new figures for this text. In addition, he helped review the page proofs. His devotion to the task of making this book student-friendly was beyond the call of duty.

Other individuals who contributed, arranged in alphabetical order, are: Mr. Mike Anderson of Nolte and Associates, reviewed portions of the text and worked several design examples; Professor Takashi Asano of the University of California at Davis, the 2001 Stockholm Water Prize recipient, revised Chap. 13, which he had contributed to the third edition; Dr. Keith Bourgeous of Carollo Engineers contributed and reviewed portions of Chap. 11; Mr. Max Burchett of Whitley Burchett & Associates in numerous discussions over many years has contributed valuable insights on the application of theory to practice; Ing. Ermanno Cacciari of Austep Environmental Protection, Milan, Italy, contributed to the section on anaerobic sludge blanket processes in Chap. 10; Dr. Robert Cooper of BioVir laboratories reviewed and provided valuable input for Chap. 2; Professor John C. Crittenden of Michigan Technological University reviewed Chap. 4 and the section on carbon adsorption in Chap. 11; Dr. Alex Ekster, of Ekster and Associates, contributed the sections on process control optimization in Chap. 15; Dr. Robert Emerick of Ecologic Engineers, contributed the section on UV disinfection in Chap. 11; Mr. William Hartnett of Montgomery/Watson contributed writeups on program logic controllers and piping and instrument diagrams in Chap. 15; Dr. Tim Haug of the City of Los Angeles reviewed and provided valuable insight on Chaps. 7 through 10 and 15; Professor David Jenkins of the University of California at Berkeley, provided photomicrographs of filamentous microorganisms; Ms. Sarah Mayhew printed most of the photographs; Ms. Margie Nellor of the County Sanitation Districts of Los Angeles County provided a photograph of the Rio Hondo spreading basins, Professor Kara Nelson of the University of California at Berkeley reviewed Chap. 2; Mr. Andrew Salveson of Whitley Burchett & Associates, reviewed Chaps. 2 and 4 and provided data for Chap. 11; Professor Edward D. Schroeder of the University of California at Davis reviewed an early draft of Chap. 7 and provided valuable organizational and technical comments and guidance, and as a colleague of 30 years, Professor Schroeder has contributed significantly to the education of the senior author; Dr. Richard E. Speece of Vanderbilt University reviewed the section on anaerobic digestion in Chap. 14 and provided valuable insight; Mr. Jeff Sollar of EOA, contributed to the probabilistic analysis of multiple processes in Chap. 13; Dr. Rhodes Trussell of Montgomery/Watson in numerous discussions offered valuable insights on disinfection, flocculation, and mixing processes; and Mr. Mike Weiner of the Orange County Water District provided a photograph of the water spreading basins in Orange County. The collective efforts of these individuals is invaluable.

Reviewers, selected by the publisher, who were asked to assess and comment on the prospectus for the fourth edition included Professor James J. Bisogni Jr. of Cornell University, Professor Alan R. Bowers of Vanderbilt University, Professor Jeff Kuo, of California State University at Fullerton, Professor Bruce Logan of Pennsylvania State University, Professor John A. Olofsson of the University of Alaska at Anchorage, and

Professor Tian C. Zhang of the University of Nebraska at Lincoln. Their input, early on, helped guide the development of the final format of the fourth edition. Their contributions are gratefully acknowledged.

The reviewers, selected by the publisher, who read the entire manuscript of the fourth edition, were Professor Syed A. Hashsham of Michigan State University; Professor Robert Lang of California Polytechnic University at San Luis Obispo; Professor John T. Novak of Virginia Polytechnic Institute and State University; and Professor Robert M. Sykes of Ohio State University. They provided valuable and timely comments that improved the content, organization, and readability of this textbook. Their contributions were significant and are acknowledged gratefully.

The assistance of the staff of Metcalf & Eddy in the preparation of this text is also acknowledged. The efforts of Mr. James Anderson were especially important in making this book possible and in managing the resources made available by Metcalf & Eddy to the authors. Mr. Jonathan Doane organized the team of staff reviewers and provided liaison between the authors and the reviewers. Valuable comments were provided that reflect current design practice in both the United States and overseas.

The McGraw-Hill staff was also critical to the production of this textbook. Mr. Eric Munson, formerly of McGraw-Hill, was instrumental in the early development of this project. Ms. Amy Hill, Developmental Editor, served as the overall project manager. Her organizational skills and tireless efforts on our behalf have made this book a reality. Her sunny personality was also a great help. Ms. Kay J. Brimeyer served as production coordinator and helped keep all of the loose ends together, while maintaining her sense of humor. Ms. Susan Sexton served as the technical editor. The publishers were Mr. Tom Casson and Ms. Betsy Jones.

Finally to Rosemary Tchobanoglous and Nancy Burton who suffered, supported, and encouraged us through the writing of this textbook, we are eternally grateful. Support for Dave Stensel by Carleen Clark and Pat Halikas was especially helpful.

George Tchobanoglous
Davis, CA

Franklin L. Burton
Los Altos, CA

H. David Stensel
Seattle, WA

Foreword

Almost 90 years have passed since Metcalf & Eddy first published *American Sewage Practice,* the legendary three-volume treatise that established design standards for sewerage facilities. Subsequently, the three volumes were combined into a single text, *Sewerage and Sewage Disposal,* in 1922 and a second edition was published in 1930 for class use in engineering schools. In 1972, a new version of the textbook was published, *Wastewater Engineering: Collection, Treatment, and Disposal,* followed in 1979 by a second edition, *Wastewater Engineering: Treatment, Disposal, Reuse.* A companion textbook, *Wastewater Engineering: Collection and Pumping of Wastewater,* was also published in 1981. The most recent publication was the third edition of *Wastewater Engineering* in 1991. Even though the wastewater practice has continued to evolve and grow during this period, no time period in the past can equal the last decade in terms of technological development.

In addition, the awareness of environmental issues among the U.S and world communities has reached a level not seen before. This active awareness is driving our industry to achieve levels of performance far beyond those envisioned even as recently as the last decade. This fourth edition of *Wastewater Engineering* incorporates these concepts as an essential part of a central theme. As a result, the fourth edition has been designed with a forward-looking focus. For example, emerging fields of biological process modeling and genetic engineering are addressed with some predictions on where these concepts may fit into future wastewater engineering activities.

Since the third edition was published in 1991, much focus in the wastewater practice has turned to nutrient removal, with particular emphasis on biological nutrient removal (BNR). Research in this field is being carried on worldwide, and new discoveries that challenge some of the conventional theory continue to be made. The chapters in the fourth edition that pertain to biological processes and BNR are therefore essentially new. They deal with both research results and their applications to wastewater engineering design.

Pressure for environmental compliance today is greater than ever. Regulatory requirements are, as always, present and forceful. Support from the community for environment-related programs is becoming a stronger driving force than ever before. *Stakeholders,* as they are often referred to, are quite demanding, well organized, and informed. They challenge wastewater engineers to stretch the performance of existing infrastructure through applied research programs. This concept, referred to by Metcalf & Eddy as "infrastretching," represents one of the most significant challenges to the practice of wastewater engineering in the new century.

ACKNOWLEDGMENTS

Metcalf & Eddy, Inc. has been privileged to have as our principal authors Dr. George Tchobanoglous of the University of California at Davis; Franklin L. Burton, a retired vice president of Metcalf & Eddy; and Dr. David Stensel of the University of Washington.

The principal authors were responsible for scope of the textbook, writing, editing, and coordination with the reviewers and the publisher. Two of our principal authors have enjoyed a long association with the textbook. The third principal author, Dr. Stensel, has joined the team for the fourth edition. Dr. Tchobanoglous was the principal author for the first three editions of this text and for the first two editions of the companion volume, *Wastewater Engineering: Collection and Pumping of Wastewater.* Mr. Burton was technical reviewer for the second edition of this text and the companion text and a principal author for the third edition.

The staff of Metcalf & Eddy played a significant role in the preparation of this edition. We acknowledge the contributions of the following members of the staff for their valuable efforts in review of manuscripts:

Kevin L. Anderson	Jonathan W. Doane
David P. Bova	Robert Gay
John G. Chalas	Charles E. Pound

We would also like to offer our sincere gratitude to Dr. Roger T. Haug for his review of the chapters that cover biological wastewater treatment processes. Dr. Haug's comments were very helpful with respect to achieving one of our goals: the presentation of wastewater engineering in a forward-looking fashion.

Special appreciation is extended to Jonathan W. Doane for his efforts in managing Metcalf & Eddy's efforts and to John G. Chalas, the former director of technology of Metcalf & Eddy, now retired, who served as special advisor.

An effort such as this fourth edition could not be successful without the professional encouragement and support of corporate management. We gratefully acknowledge the contributions of Robert H. Fisher, chairman and CEO of Metcalf & Eddy, Inc., and John Somerville, president of Metcalf & Eddy. We would also like to acknowledge the vision of our parent company, AECOM Technologies, Inc., acting through Richard Newman, chairman, and Raymond Holdsworth, president, for the commitment they made to complete this effort and to pave the way for future editions.

Metcalf & Eddy would like to make special note of the passing in 2001 of Harry L. Kinsel, a former president of Metcalf & Eddy. Harry Kinsel was known for his professionalism and commitment to education. Metcalf & Eddy established an internal competition for technical papers in 1973 in Harry Kinsel's honor and this competition will continue as an inspiration to Metcalf & Eddy staff and the industry.

Finally, I would like to personally express my appreciation to the entire team of authors, editors, and reviewers for their tireless effort, and the senior management of Metcalf & Eddy, Inc., and AECOM Technologies, Inc., for the opportunity to direct this effort for Metcalf & Eddy.

James Anderson
Senior Vice President
Chief Engineer
Metcalf & Eddy, Inc.

Contents

Preface xxi
Acknowledgments xxv
Foreword xxvii

1 Wastewater Engineering: An Overview 1

1-1 Terminology 3
1-2 Impact of Regulations on Wastewater Engineering 3
1-3 Health and Environmental Concerns in Wastewater Management 7
1-4 Wastewater Characteristics 9
Improved Analytical Techniques 10
Importance of Improved Wastewater Characterization 10
1-5 Wastewater Treatment 10
Treatment Methods 11
Current Status 12
New Directions and Concerns 15
Future Trends in Wastewater Treatment 20
1-6 Wastewater Reclamation and Reuse 20
Current Status 21
New Directions and Concerns 21
Future Trends in Technology 21
1-7 Biosolids and Residuals Management 22
Current Status 22
New Directions and Concerns 23
Future Trends in Biosolids Processing 23

2 Constituents in Wastewater 27

2-1 Wastewater Constituents 29
Constituents Found in Wastewater 29
Constituents of Concern in Wastewater Treatment 29
2-2 Sampling and Analytical Procedures 29
Sampling 29
Methods of Analysis 34
Units of Measurement for Physical and Chemical Parameters 35
Useful Chemical Relationships 35
2-3 Physical Characteristics 42
Solids 42
Particle Size Distribution 48
Turbidity 51
Color 52
Absorption/Transmittance 52
Temperature 54
Conductivity 56
Density, Specific Gravity, and Specific Weight 56
2-4 Inorganic Nonmetallic Constituents 57
pH 57
Chlorides 59
Alkalinity 59
Nitrogen 60
Phosphorus 63
Sulfur 64
Gases 64
Odors 70
2-5 Metallic Constituents 77
Importance of Metals 77
Sources of Metals 77
Sampling and Methods of Analysis 77
Typical Effluent Discharge Limits for Metals 78
2-6 Aggregate Organic Constituents 80
Measurement of Organic Content 81
Biochemical Oxygen Demand (BOD) 81
Total and Soluble Chemical Oxygen Demand (COD and SCOD) 93
Total and Dissolved Organic Carbon (TOC and DTOC) 94
UV-Absorbing Organic Constituents 95

Theoretical Oxygen Demand (ThOD) 96
Interrelationships between BOD, COD, and TOC 96
Oil and Grease 98
Surfactants 98
2–7 Individual Organic Compounds 99
Priority Pollutants 99
Analysis of Individual Organic Compounds 100
Volatile Organic Compounds (VOCs) 100
Disinfection Byproducts 102
Pesticides and Agricultural Chemicals 102
Emerging Organic Compounds 102
2–8 Biological Characteristics 104
Microorganisms Found in Surface Waters and Wastewater 104
Pathogenic Organisms 109
Use of Indicator Organisms 115
Enumeration and Identification of Bacteria 118
Enumeration and Identification of Viruses 126
Polymerase Chain Reaction (PCR) 129
Development of Microorganisms Typing Techniques 130
New and Reemerging Microorganisms 130
2–9 Toxicity Tests 130
Toxicity Terminology 131
Toxicity Testing 133
Analysis of Toxicity Test Results 134
Application of Toxicity Test Results 136
Identification of Toxicity Components 137

3 Analysis and Selection of Wastewater Flowrates and Constituent Loadings 153
3–1 Components of Wastewater Flows 154
3–2 Wastewater Sources and Flowrates 154
Domestic Wastewater Sources and Flowrates 155
Strategies for Reducing Interior Water Use and Wastewater Flowrates 158
Water Use in Developing Countries 162
Sources and Rates of Industrial (Nondomestic) Wastewater Flows 162
Infiltration/Inflow 163
Exfiltration from Collection Systems 167
Combined System Flowrates 168
3–3 Statistical Analysis of Flowrates, Constituent Concentrations, and Mass Loadings 170
Common Statistical Parameters 170
Graphical Analysis of Data 171
3–4 Analysis of Wastewater Flowrate Data 178
Definition of Terms 178
Variations in Wastewater Flowrates 179
Wastewater Flowrate Factors 180
3–5 Analysis of Constituent Mass Loading Data 181
Wastewater Constituent Concentrations 181
Variations in Constituent Concentrations 185
Flow-Weighted Constituent Concentrations 192
Calculation of Mass Loadings 194
Effect of Mass Loading Variability on Treatment Plant Performance 197
3–6 Selection of Design Flowrates and Mass Loadings 197
Design Flowrates 199
Design Mass Loadings 205

4 Introduction to Process Analysis and Selection 215
4–1 Reactors Used for the Treatment of Wastewater 218
Types of Reactors 218
Application of Reactors 220
Hydraulic Characteristics of Reactors 220
4–2 Mass-Balance Analysis 222
The Mass-Balance Principle 222
Preparation of Mass Balances 224
Application of the Mass-Balance Analysis 224
Steady-State Simplification 225
4–3 Modeling Ideal Flow in Reactors 226
Ideal Flow in Complete-Mix Reactor 226
Ideal Flow in Plug-Flow Reactor 227

4–4 Analysis of Nonideal Flow in Reactors Using Tracers 229
Factors Leading to Nonideal Flow in Reactors 229
Need for Tracer Analysis 231
Types of Tracers 231
Conduct of Tracer Tests 231
Analysis of Tracer Response Curves 233
Practical Interpretation of Tracer Measurements 242
4–5 Modeling Nonideal Flow in Reactors 245
The Distinction between Molecular Diffusion, Turbulent Diffusion, and Dispersion 245
Plug-Flow Reactor with Axial Dispersion 246
Complete-Mix Reactors in Series 252
4–6 Reactions, Reaction Rates, and Reaction Rate Coefficients 257
Types of Reactions 257
Rate of Reaction 258
Reaction Order 259
Types of Rate Expressions 260
Rate Expressions Used in Environmental Modeling 261
Effects of Temperature on Reaction Rate Coefficients 261
Analysis of Reaction Rate Coefficients 264
4–7 Modeling Treatment Process Kinetics 269
Batch Reactor with Reaction 269
Complete-Mix Reactor with Reaction 270
Complete-Mix Reactors in Series with Reaction 271
Ideal Plug-Flow Reactor with Reaction 274
Comparison of Complete-Mix and Plug-Flow Reactors with Reaction 275
Ideal Plug-Flow Reactor with Retarded Reaction 277
Plug-Flow Reactor with Axial Dispersion and Reaction 279
Other Reactor Flow Regimes and Reactor Combinations 281
4–8 Treatment Processes Involving Mass Transfer 283
Basic Principle of Mass Transfer 283
Gas-Liquid Mass Transfer 284
Liquid-Solid Mass Transfer 293
4–9 Introduction to Process Selection 297
Important Factors in Process Selection 297
Process Selection Based on Reaction Kinetics 299
Process Selection Based on Mass Transfer 300
Process Design Based on Loading Criteria 301
Bench Tests and Pilot-Plant Studies 301
Reliability Considerations in Process Selection 301

5 Physical Unit Operations 311
5–1 Screening 315
Classification of Screens 315
Coarse Screens (Bar Racks) 316
Fine Screens 322
Microscreens 326
Screenings Characteristics and Quantities 327
5–2 Coarse Solids Reduction 330
Comminutors 331
Macerators 332
Grinders 333
Design Considerations 333
5–3 Flow Equalization 333
Description/Application 333
Design Considerations 335
5–4 Mixing and Flocculation 344
Continuous Rapid Mixing in Wastewater Treatment 345
Continuous Mixing in Wastewater Treatment 345
Energy Dissipation in Mixing and Flocculation 347
Timescale in Mixing 350
Types of Mixers Used for Rapid Mixing in Wastewater Treatment 350
Types of Mixers Used for Flocculation in Wastewater Treatment 355
Types of Mixers Used for Continuous Mixing in Wastewater Treatment 359