Wastewater Engineering

Treatment and Resource Recovery

Fifth Edition

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Metcalf & Eddy | AECOM

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George Tchobanoglous is Professor Emeritus in the Department of Civil and Environmental Engineering at the University of California, 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. from Stanford University in 1969. Dr. Tchobanoglous' research interests are in the areas of wastewater treatment and reuse, wastewater filtration, UV disinfection, aquatic wastewater management systems, wastewater management for small and decentralized wastewater management systems, and solid waste management. He has authored or co-authored over 500 technical publications including 22 textbooks and 8 reference works. The textbooks are used in more than 225 colleges and universities, by practicing engineers, and in universities worldwide both in English and in translation. His books are famous for successfully bridging the gap between academia and the day-to-day world of the engineer. He is a Past President of the Association of Environmental Engineers and Science Professors. Among his many honors, in 2003 Professor Tchobanoglous received the Clarke Prize from the National Water Research Institute. In 2004, he received the Distinguished Service Award for Research and Education in Integrated Waste Management from the Waste-To-Energy Research and Technology Council. In 2004, he was also inducted into the National Academy of Engineering. In 2005, he was awarded an honorary Doctor of Engineering from the Colorado School of Mines. In 2007, he received the Frederick George Pohland Medal awarded by AAEE and AEESP. In 2012 he was made a WEF Fellow. He is a registered Civil Engineer in California.

H. David Stensel is a Professor in the Civil and Environmental Engineering Department 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, resource recovery, and biodegradation of micropollutants. He is a Past Chair of the Environmental Engineering Division of ASCE, has served on the board of the Association of Environmental Engineering Professors and on various committees for ASCE and the Water Environment Federation. He has authored or coauthored over 150 technical publications and a textbook on biological nutrient removal. Research recognition honors include the ASCE Rudolf Hering Medal, the Water Environment Federation Harrison Prescott Eddy Medal twice, and the Bradley Gascoigne Medal. In 2013, he received the Frederick George Pohland Medal awarded by AAEE and AEESP. He is a registered professional engineer, a diplomate in the American Academy of Environmental Engineers and a life member of the American Society of Civil Engineers and the Water Environment Federation.

Ryujiro Tsuchihashi is a technical leader with AECOM. He received his B.S. and M.S. in civil and environmental engineering from Kyoto University, Japan, and a Ph.D. in environmental engineering from the University of California, Davis. The areas of his expertise include wastewater/water reclamation process evaluation and design, evaluation and assessment of water reuse systems, biological nutrient removal, and evaluation of greenhouse gas emission reduction from wastewater treatment processes. He was a co-author of the textbook "Water Reuse: Issues, Technologies and Applications," a companion textbook to this textbook. He is a technical practice coordinator for AECOM's water reuse leadership team. Ryujiro Tsuchihashi is a member of the Water Environment Federation, American Society of Civil Engineer, and International Water Association, and has been an employee of AECOM for 10 years, during which he has worked on various projects in the United State, Australia, Jordan, and Canada.

Franklin Burton served as vice president and chief engineer of the western region of Metcalf & Eddy in Palo Alto, California for 30 years. He retired from Metcalf & Eddy in 1986 and has been in private practice in Los Altos, California, specializing in treatment technology evaluation, facilities design review, energy management, and value engineering. He received his B.S. in mechanical engineering from Lehigh University and an M.S. in civil engineering from the University of Michigan. He was co-author of the third and fourth editions of the Metcalf & Eddy textbook "Wastewater Engineering: Treatment and Reuse." He has authored over 30 publications on water and wastewater treatment and energy management in water and wastewater applications. He is a registered civil engineer in California and is a life member of the American Society of Civil Engineers, American Water Works Association, and Water Environment Federation.

Mohammad Abu-Orf is AECOM's North America biosolids practice leader and wastewater director. He received his B.S. in civil engineering from Birzeit University, West Bank, Palestine and received his M.S. and Ph.D. in civil and environmental engineering from the University of Delaware. He worked with Siemens Water Technology and Veolia Water as biosolids director of research and development. He is the main inventor on five patents and authored and co-authored more than 120 publications focusing on conditioning, dewatering, stabilization and energy recovery from biosolids. He was awarded first place for Ph.D. in the student paper competition by the Water Environment Federation for two consecutive years in 1993 and 1994. He coauthored manuals of practice and reports for the Water Environment Research Foundation. He served as an editor of the Specialty Group for Sludge Management of the International World Association for six years and served on the editorial board of the biosolids technical bulletin of the Water Environment Federation. Mohammad Abu-Orf has been an employee of AECOM for 6 years.

Gregory Bowden is a technical leader with AECOM. He received his B.S. in chemical engineering from Oklahoma State University and a Ph.D. in chemical engineering from the University of Texas at Austin. He worked for Hoechst Celanese (Celanese AG) for 10 years as a senior process engineer, supporting wastewater treatment facility operations at chemical production plants in North America. He also worked as a project manager in the US Filter/Veolia North American Technology Center. His areas of expertise include industrial wastewater treatment, biological and physical/chemical nutrient removal technologies and biological process modeling. Greg Bowden is a member of the Water Environment Federation and has been an AECOM employee for 9 years.

William Pfrang is a Vice-President of AECOM and Technical Director of their Metro-New York Water Division. He began his professional career with Metcalf & Eddy, Inc., as a civil engineer in 1968. During his career, he has specialized in municipal wastewater treatment plant design including master planning, alternative process assessments, conceptual, and detailed design. Globally, he has been the lead engineer for wastewater treatment projects in the United States, Southeast Asia, South America, and the Middle East. He received his B.S. and M.S. in civil engineering from Northeastern University. He is a registered professional engineer, a member of the American Academy of Environmental Engineers, and the Water Environment Federation. William Pfrang has been an employee of the firm for over 40 years.

Contents

Appendixes

Indexes

Preface

Since completion of the fourth edition of this textbook, the field of wastewater engineering has evolved at a rapid pace. Some of the more significant changes include:

1. A new view of wastewater as a source of energy, nutrients, and potable water.
2. More stringent discharge requirements related to nitrogen and phosphorus;
3. Enhanced understanding of the fundamental microbiology and physiology of the microorganisms responsible for the removal of nitrogen and phosphorus and other constituents;
4. An appreciation of the importance of the separate treatment of return flows with respect to meeting more stringent standards for nitrogen removal and opportunities for nutrient recovery,
5. Increased emphasis on the treatment of sludge and the management of biosolids; and
6. Increased awareness of carbon footprint impacts and greenhouse gas emissions, and an emphasis on the development of energy-neutral or energy-positive wastewater plants through more efficient use of chemical and heat energy in wastewater.

The 5th edition of this textbook has been prepared to address the significant changes cited above. Increased understanding of the importance of pre-treatment processes is addressed in Chap. 5. Advances in biological treatment are addressed in Chaps. 7 through 10. New developments in disinfection are considered in Chap. 12. The management of sludge and biosolids is now covered in Chaps. 13 and 14. Return flow treatment is considered in Chap. 15. Energy management is considered in Chap. 17. An emphasis of this fifth edition is to present practical design and operational data, while maintaining a solid theoretical discussion of the technologies and applications. Input from AECOM's process engineers and outside reviewers was sought to provide the user with a source of real-world practical information, the likes of which is not available in any single source.

IMPORTANT FEATURES OF THIS BOOK

In the 4th edition of this book, a separate chapter was devoted to the fundamentals of process analysis, including an introduction to the preparation of mass balances and reaction kinetics. Because introductory courses on process analysis and modeling are now taught at most colleges and universities, the material on the fundamentals of process analysis from the 4th edition has been condensed and is now included in Secs. 1–7 through 1–11 in Chap. 1. The material on process analysis has been retained as a reference source for students that have already had a separate course on modeling and as an introduction to the subject for students who may not have had an introductory course.

Following the practice in the 4th edition, more than 150 example problems have been worked out in detail to enhance the readers' understanding of the basic concepts presented in the text. To aid in the planning, analysis, and design of wastewater management systems, design data and information are summarized and presented in more than 400 tables, most of which are new. To illustrate the principles and facilities involved in the field of wastewater management, over 850 individual illustrations, graphs, diagrams, and photographs are included. An additional 120 drawings are included in tables. More than 375 homework problems and discussion topics are included to help the readers of this textbook hone their analytical skills and enhance their mastery of the material. Extensive references are also provided for each chapter.

The International System (SI) of Units is used in the 5th edition. The use of SI units is consistent with teaching practice in most US universities and in most countries throughout the world. In general, dual sets of units (i.e., SI and US 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 US Customary Units and the reverse are presented in Appendixes A–1 and A–2, respectively. Conversion factors used commonly for the analysis and design of wastewater management systems are presented in Appendix A–3. Abbreviations for SI and US 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. The statistical analysis is reviewed in Appendix D. Dissolved oxygen concentrations in water as a function of temperature are presented in Appendix E. Carbonate equilibrium is considered in Appendix F. Moody diagrams for the analysis of flow in pipes are presented in Appendix G. The analysis of nonideal flow in reactors is considered in Appendix H. Modeling nonideal flow in reactors is addressed in Appendix I.

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 book can be used both as a class textbook or class reference to supplement instructors' notes. The specific topics to be covered will depend on the time available and the course objectives. Suggested course outlines are presented below.

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

Topic	Chapter	Sections
Introduction to wastewater treatment	1	1–1 to1–6
Wastewater characteristics	2	All
Wastewater flowrates and constituent loadings	3	All
Physical unit processes	5	5–1 to 5–8
Chemical unit processes	6	6–1 to 6–3
Introduction to biological treatment of wastewater	7	All
Disinfection	12	12–1 to 12–5, 12–9
Biosolids management	13, 14	All
Process selection, design, and implementation	4	All
Advanced treatment processes (optional)	6, 11	6–7, 6–8, 11–5 to 11–7

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

Topic	Chapter	Sections
Introduction to wastewater treatment	1	1–1 to1–6
Wastewater characteristics	2	All
Wastewater flowrates and constituent loadings	3	All
Process selection, design, and implementation	4	4–1 to 4–5
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 treatment processes	10	10–1 to 10–5
Disinfection	12	All
Sludge Management	13	All
Biosolids management	14	All
Treatment of return flows	15	All

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

Topic	Chapter	Sections
Introduction to wastewater treatment	1	1–1 to1–6
Wastewater characteristics	2	All
Process selection, design, and implementation	4	4–2, 4–4, 4–5
Introduction to biological treatment of wastewater	7	7–1 to 7–8
Suspended growth processes	8	8–1 to 8–3
Attached growth biological treatment processes	9	All
Anaerobic treatment processes	10	10–1 to 10–5
Anaerobic sludge treatment	13	13–9, 13–10

For a one semester course on physical and chemical unit 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
Process selection, design, and implementation	4	4–1 to 4–4
Introduction to physical unit processes		
Mixing and flocculation	5	5–3
Sedimentation	5	5–4, 5–6, 5–7,
Gas transfer	5	5–10, 5–11
Filtration (conventional depth filtration)	11	11–3, 11–4, 11–6
Membrane filtration	11	11–7
Adsorption	11	11–9
Gas stripping	11	11–10
UV disinfection	12	12–9
Introduction to chemical unit processes		6–2
Coagulation	6	6–2
Chemical precipitation	6	6–3, 6–4, 6–6
Ion exchange	11	11–11
Water stabilization	6	6–10
Chemical oxidation (conventional)	6	6–7
Advanced oxidation processes	6	6–8
Photolysis	6	6–9

Acknowledgments

This textbook is a tribute to the engineers and scientists who continue to push forward the practice and technologies of the wastewater industry. These advances continue to offer the world cleaner water resources and sustainable water supplies. The book could not have been written without the efforts of numerous individuals including the primary writers, contributing authors, individuals with specialized skills, technical reviewers, outside reviewers, and practitioners who contributed real life experiences.

Contributing authors from AECOM included: Dr. Mohammad Abu-Orf who revised and updated Chaps. 13 and 14, Dr. Gregory Bowden who wrote Chap. 15, and Mr. William Pfrang who revised and updated Chap. 5. Their assistance is acknowledged gratefully. Dr. Harold Leverenz of the University of California at Davis, is singled out for special acknowledgment for extraordinary contributions to the development of the graphics used throughout the text, the revision of Chap. 6, and individual section write ups. Others deserving special acknowledgment, in alphabetical order, are: Mr. Russel Adams an environmental consultant provided comprehensive reviews of Chaps. 3, 11, and 12; Dr. Heidi Gough of the University of Washington wrote the molecular biology section of Chap. 7; Dr. April Gu of Northeastern University who helped write and provided material for Chap. 9; Ms. Emily Legault of HDR Engineers provided thoughtful and comprehensive reviews of Chaps. 2, 3, 7, 8, 11, and 12; Mr. Mladen Novakovic of AECOM contributed to the development of Chap. 5; Mr. Terry Goss of AECOM contributed extensively to the development of Chaps. 13 and 14; and Mr. Dennis Totzke of Applied Technologies had significant involvement in the development of Chap. 10.

The review of the manuscript was critical to maintain the quality of the text. Outside reviewers, arranged alphabetically, who provided critical reviews included: Dr. Onder Caliskaner of Kennedy/Jenks Consultants reviewed portions of Chap. 11; Dr. Robert Cooper of BioVir laboratories reviewed the section on microbiology in Chap. 2; Ms. Libia Diaz of the University of California at Davis reviewed the homework problems; Dr. Robert Emerick of Stantec Engineers, reviewed the section on UV disinfection in Chap. 12; Dr. David Hokanson of Trussell Technologies reviewed portions of Chap. 11; Ms. Amelia Holmes of University of California at Davis reviewed the homework problems; Dr. Kurt Ohlinger of Sacramento Regional County Sanitation District provided review for phosphorus recovery. Dr. Edward Schroeder professor emeritus of the University of California at Davis reviewed portions of Chaps. 1 and 2.

A number of current and former AECOM engineers contributed to the development of the manuscript by providing design information and by reviewing specific portions of the text. Listed in alphabetical order they are:

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George Tchobanoglous
H. David Stensel
Ryujiro Tsuchihashi
Franklin Burton

Foreword

One hundred years have passed since the three-volume "American Sewerage Practice" treatise was published in 1914–1915 by Leonard Metcalf and Harrison P. Eddy. The initial publication quickly became the standard of care and established the foundation for modern wastewater treatment. The original concept of combining theory with a strong compliment of practical data and design guidance continues on in the fifth edition. The wealth of practical information continues to be a cornerstone of Metcalf & Eddy publications, and has led to its reputation as the number one wastewater practice textbook. In this fifth edition over 150 example problems and over 375 homework problems are provided.

The textbook has become a widely used teaching resource for universities and colleges and a reference for engineering firms throughout the world and is now published in Chinese, Greek, Italian, Japanese, Korean, and Spanish.

New advances in technology continue to occur at a record pace in all fields including wastewater treatment. As a result this fifth edition includes numerous advances and represents the current state of the art information. AECOM takes great pride in presenting this Metcalf & Eddy textbook, a comprehensive compilation of the best wastewater practices in use today.

The manuscript was developed by a team of primary writers including Dr. George Tchobanoglous, Dr. H. David Stensel, Dr. Ryujiro Tsuchihashi, Dr. Mohammad Abu-Orf, Mr. William Pfrang and Dr. Gregory Bowden. In addition to our primary authors, over 55 AECOM employees and outside technical specialists contributed in reviews and provided practical data and guidance.

I would also like to acknowledge Mr. Bill Stenquist, Executive Editor, McGraw-Hill, who was instrumental in bringing the resources of McGraw-Hill to this project.

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