WATER REUSE

ISSUES, TECHNOLOGIES, AND APPLICATIONS

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Issues, Technologies, and Applications

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This book is dedicated to Metcalf & Eddy's James Anderson, who died of cancer in March 2006 and was therefore unable to see this book through to publication.

As Director of Technology, Jim was responsible for Metcalf & Eddy's research program and for the continued development of our textbooks. It was through his vision of the importance of water reuse in strategic water resources management that this book was brought to fruition. Jim also understood the need to train environmental engineering professionals and Metcalf & Eddy's commitment to do its part as originally conceived and carried out by Leonard Metcalf and Harrison P. Eddy nearly 100 years ago.

Steve Guttenplan
President
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George Tchobanoglous is a 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. His 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 coauthored over 350 technical publications including 13 textbooks and 4 reference works. The textbooks are used in more than 225 colleges and universities, as well as by practicing engineers. The textbooks have also been used extensively in universities worldwide both in English and in translation. He is a past president of the Association of Environmental Engineering and Science Professors. Among his many honors, in 2003 Professor Tchobanoglous received the Clarke Prize from the National Water Research Institute. In 2004, he was inducted into the National Academy of Engineering. In 2005, he received an Honorary Doctor of Engineering Degree from the Colorado School of Mines. He is a registered civil engineer in California.

Contents

Preface

With many communities approaching the limits of their available water supplies, water reclamation and reuse has become a logical option for conserving and extending available water supply by potentially (1) substituting reclaimed water for applications that do not require drinking (potable) water, (2) augmenting existing water sources and providing an additional source of water supply to assist in meeting both present and future water needs, (3) protecting aquatic ecosystems by decreasing the diversion of freshwater as well as reducing the quantity of nutrients and other toxic contaminants entering waterways, (4) postponing and reducing the need for water control structures, and (5) complying with environmental regulations by better managing water consumption and wastewater discharges. The increasing importance and recognition of water reclamation and reuse have led to the need for specialized instruction of engineering and science students in their undergraduate and graduate levels, as well as practicing engineers and scientists, and a technical reference for project managers and government officials. Aside from the need for a textbook on water reuse applications and the technologies used to treat and distribute reclaimed water, there is also the need to address the special considerations of public health, project planning and economics, public acceptance, and the diverse uses of reclaimed water in society.

ORGANIZATION OF THE TEXTBOOK AND CONTENT

This textbook, *Water Reuse: Issues, Technologies, and Applications*, is an endeavor by the authors to assemble, analyze, and synthesize a vast amount of information on water reclamation and reuse. To deal with the amount of available material, the book is organized into five parts, each dealing with a coherent body of information which is described below.

Part 1: Water Reuse: An Introduction

It is important to understand the concept of sustainable water resources management as a foundation for water reclamation and reuse. Thus, in Part 1 of this textbook, current and potential future water shortages, principles of sustainable water resources management, and the important role of water reclamation and reuse are introduced briefly. The past and current practices of water reclamation and reuse are presented, which also serve as an introduction to the subsequent engineering and water reuse applications chapters.

Part 2: Health and Environmental Concerns in Water Reuse

Health and environmental issues related to water reuse are discussed in three related chapters in Part 2. The characteristics of wastewater are introduced, followed by a discussion of the applicable regulations and their development. Because health risk analysis is an important aspect of water reuse applications, a separate chapter is devoted to this subject including tools and methods used in risk assessment, chemical risk assessment, and microbial risk assessment.

Part 3: Water Technologies and Systems for Water Reclamation and Reuse

The various technologies and systems available for the production and delivery of reclaimed water are the subject of Part 3. Although design values are presented, detailed design is not the focus of these chapters. Rather, the focus is on the dependable performance of the processes and technologies. Detailed discussions are provided with respect to constituents of concern in water reuse applications including particulate matter, dissolved constituents, and pathogenic microorganisms. Another important aspect of water reclamation is related to meeting stringent water quality performance requirements as affected by wastewater variability and process reliability, factors which are emphasized repeatedly throughout this textbook.

Part 4: Water Reuse Applications

Because water quality and infrastructure requirements vary greatly with specific water reuse application, major water reuse applications are discussed in separate chapters in Part 4: nonpotable water reuse applications including agricultural uses, landscape irrigation, industrial uses, environmental and recreational uses, groundwater recharge, and urban nonpotable and commercial uses. Indirect and direct potable reuses are discussed with several notable projects. Groundwater recharge can be considered as a form of indirect potable reuse if the recharged aquifer is interconnected to potable water production wells.

Part 5: Implementing Water Reuse

In the final Part 5 of this textbook, the focus is on planning and implementation for water reuse. Integrated water resources planning, including reclaimed water market assessment, and economic and financial analyses are presented. As technology continues to advance and cost effectiveness and the reliability of water reuse systems becomes more widely recognized, water reclamation and reuse plans and facilities will continue to expand as essential elements in sustainable water resources management. Implementation issues in water reclamation and reuse are discussed including soliciting and responding to community concerns, development of public support through educational programs, and the development of financial instruments.

IMPORTANT FEATURES OF THIS TEXTBOOK

To illustrate the principles, applications, and facilities involved in the field of water reclamation and reuse, more than 350 data and information tables and 80 detailed worked examples, more than 500 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 this textbook. The use of SI units is consistent with teaching practice in most universities in the United States and in most countries throughout the world.

To further increase the utility of this textbook, several appendixes have been included. Conversion factors from SI Units to U.S. 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 water and 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. Statistical analysis of data with an example is presented in Appendix D.

Milestone water reuse projects and research studies in the United States and a summary of water reclamation and reuse in selected countries of the world are presented in Appendixes E-1 and E-2, respectively. Evolution of nonpotable reuse criteria and groundwater recharge regulations in California is presented in Appendix F. Dimensionless well function W(u) values are presented in Appendix G. Finally, interest factors and their use are presented and illustrated in Appendix H.

With recent Internet developments, it is now possible to view many of the facilities discussed in this textbook through satellite images using one of the many search engines available on the Internet. Where appropriate, global positioning coordinates for water reuse facilities of interest are given to allow viewing of these facilities in their natural setting.

USE OF THIS TEXTBOOK

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. Three suggested course plans are presented below.

Course Plan I

Course Title:	Survey of Water Reuse
Setting:	1 semester or 1 quarter, stand-alone class
Target:	Upper division or MS, environmental science major
Course Objectives:	Introduce important considerations influencing water reuse planning and implementation.

Sample outline:

Topic	Chapters	Sections
Introduction to water reuse	1, 2	All
Wastewater characteristics	3	3-1, 3-2, 3-5 to 3-8
Regulations for water reuse	4	4-1 to 4-7
Public health protection and risk assessment	5	5-1 to 5-5, 5-9
Introduction to water reclamation technologies	6	All
Infrastructure for water reuse	12, 13, 14, 15	12-1, 12-2, 13-1, 13-2, 13-6, 14-1, 14-2, 15-1, 15-2
Overview of disinfection for reuse applications	11	11-1, 11-2
Introduction to water reuse applications	16	All
Perspectives on water reuse planning	25	25-1 to 25-4
Perspectives on public acceptance	26	26-1 to 26-3

Course Plan II

Course Title:	Water Reuse Applications
Setting:	1 semester or 1 quarter class
Target:	Upper division or MS, environmental engineering major
Course Objectives:	Introduce nonconventional engineering aspects of water reuse including satellite, decentralized, and onsite treatment and reuse systems. An overview of various water reuse applications are introduced.

Sample outline:

Topic	Chapters	Sections
Introduction to water reclamation and reuse	1, 2	1-1 to 1-5, 2-1
Wastewater characteristics	3	3-1, 3-2, 3-5 to 3-8
Water reuse regulations and guidelines	4	4-1 to 4-4, 4-6 to 4-8
Public health protection and risk assessment	5	5-1 to 5-5, 5-8, 5-9
Introduction to water reclamation technologies	6	6-1 to 6-5
Overview of disinfection for reuse applications	11	11-1, 11-2
Introduction to water reuse applications	16	All
Reclaimed water use for irrigation	17, 18	17-1 to 17-3, 18-1 to 18-2, 18-4 to 18-5
Reclaimed water use for industrial processes	19	19-1 to 19-3
Urban nonirrigation, environmental, and recreational uses	20, 21	20-1, 20-2, 21-1
Indirect potable reuse by groundwater and surface water augmentation	22, 23	22-1 to 22-2, 22-7, 23-1 to 23-3, 23-8
Economic and financial analysis	25	25-6 to 25-9
Public participation and public acceptance	25, 26	25-3, 26-1 to 26-3

Course Plan III

Course Title:	Advanced Treatment Technologies and Infrastructure for Water Reuse Applications
Setting:	1 semester or 1 quarter class
Target:	MS level, environmental engineering major
Course Objectives:	Introduce treatment technologies important in water reuse. Introduce reliability issues, concept of probability distribution in assessing disinfection performance, and future directions. The course will be a stand-alone class on advanced treatment, or part of a wastewater treatment class that covers both conventional and advanced technologies emphasizing water reclamation, recycling, and reuse. This textbook is a useful supplement to a companion textbook, *Wastewater Engineering: Treatment and Reuse*, 4th ed., (Tchobanoglous, G., F.L. Burton, and H.D. Stensel) for the following topics:

Sample outline:

Topic	Chapters	Sections
Introduction to water reuse	1, 2	All
Wastewater characteristics	3	3-1, 3-2, 3-5 to 3-8
Introduction to water reclamation and reuse	6, 16	6-2 to 6-4, 16-1 to 16-4
Membrane filtration, membrane bioreactor	7, 8	7-5, 7-6, 8-5
Nanofiltration, reverse osmosis, and electrodialysis	9	9-1 to 9-4
Adsorption, Advanced oxidation	10	10-1, 10-2, 10-6, 10-7
Disinfection	11	11-1 to 11-3, 11-5, 11-6, 11-8
Alternative systems for water reuse	12, 13	12-1, 12-2, 13-1, 13-2, 13-6,
Infrastructure for water reuse	14, 15	14-1, 14-2, 15-1 to 15-3

Acknowledgments

This textbook, *Water Reuse: Issues, Technologies, and Application* is a tribute to the pioneering planners and engineers who were able to look ahead of their time and push forward the frontiers of water reclamation and reuse from obscure practice to a growing discipline in sustainable water resources management. Based on the widespread acceptance of water reuse and the development of new treatment technologies and applications, it is an appropriate time to produce a comprehensive textbook on the subject. A book of this magnitude, however, could not have been written without the assistance of numerous individuals, some are acknowledged below and others who remain in the background. The authors are particularly grateful to many individuals who contributed the information through personal contacts and the "grey" literature as well as conference and symposium proceedings.

The principal authors were responsible for writing, editing, coordinating, and also responding to reviewer's comments for this textbook. Individuals who contributed specifically to the chapters, listed in chapter order, included Dr. James Crook, environmental engineering consultant, who prepared Chapter 4, Water Reuse Regulations and Guidelines; Dr. Joseph Cotruvo, J. Cotruvo Associates, prepared chemical risk assessment, and Dr. Adam W. Olivieri, Eisenberg Olivieri & Associates and Mr. Jeffery A. Soller, Soller Environmental, prepared microbial risk assessment in Chapter 5, Health Risk Analysis in Water Reuse Applications; Mr. Max E. Burchett of Whitley Burchett & Associates prepared Chapter 14, Storage and Distribution of Reclaimed Water; Professor Audrey D. Levine of the University of South Florida prepared portions of Chapter 19, Industrial and Commercial Uses of Reclaimed Water; Professor Peter Fox of Arizona State University prepared Chapter 22, Groundwater Recharge with Reclaimed Water; Mr. Richard A. Mills of California State Water Resources Control Board prepared Chapter 25, Planning for Water Reclamation and Reuse. The help and assistance of Mr. Pier Mantovani in the formative stage of the textbook preparation is also acknowledged. A significant contributor to preparation of this textbook was Ms. Jennifer Cole Aieta of Aieta Cole Enterprises who edited and provided insightful commentary for all of the chapters.

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San Luis Obispo, California, provided information for Chapter 21; Mr. Bruce Durham of Veolia, UK, provided materials for Chapter 24; Mr. Jeffery Goldberg, City of St. Petersburg, reviewed part of Chapter 18; Dr. Stephen Grattan, the University of California, Davis, reviewed Chapter 17; Ms. Lori Kennedy, University of California, Davis, who helped compiling information and drafted portions of Chapters 1, 2, and 25; Mr. Tze Weng Kok, Singapore Public Utilities Board reviewed portions of Chapter 24; Professor Naoyuki Funamizu of Hokkaido University in Japan reviewed portions of Chapter 5 and also provided water reuse pictures; Dr. Josef Lahnsteiner, WABAG in Austria and Dr. Günter G. Lempert, Aqua Services & Engineering (Pty) Ltd. in Namibia reviewed and contributed to Chapter 24; Messrs Gary Myers and John Bowman, Serrano El Dorado Owners' Association, California, provided materials used in Chapters 14 and 18; Professor Slawomir W. Hermanowicz of the University of California, Berkeley reviewed Chapter 1; Professor Audrey D. Levine of the University of South Florida reviewed Chapters 1 and 2; Dr. Loretta Lohman of Colorado State University Cooperative Extension reviewed Chapter 26; Professor Rafael Mujeriego of Technical University of Catalonia in Spain in numerous discussions over many years has contributed valuable insight; Dr. Kumiko Oguma of the University of Tokyo in Japan reviewed portions of Chapter 11 and provided information on microbial regrowth in UV disinfection; Professor Choon Nam Ong of the National University of Singapore reviewed portions of Chapter 24; Professor Gideon Oron, Ben-Gurion University of the Negev in Israel provided irrigation pictures; Mr. Erick Rosenblum, City of San Jose, California, reviewed portions of Chapter 26; Dr. Bahman Sheikh, water reclamation consultant, reviewed Chapters 17, 23, and 24; Messrs. Keiichi Sone and Toshiaki Ueno of the Tokyo Metropolitan Government in Japan provided several water reuse pictures used in Chapters 20 and 21; Professor H. David Stensel of the University of Washington reviewed Chapters 6 and 7; Mr. Tim Sullivan, El Dorado Irrigation District, California, provided information and reviewed portions of Chapter 18; Professor Kenneth Tanji of the University of California, Davis, reviewed Chapter 17; Mr. Thai Pin Tan of Singapore Public Utilities Board reviewed portions of Chapter 24 and provided the information; Professor Hiroaki Tanaka of Kyoto University in Japan reviewed microbial risk assessment sections of Chapter 5; Dr. R. Shane Trussell reviewed and provided valuable comments on membrane bioreactors in Chapter 7; Professor Gedaliah Shelef of the Israel Institute of Technology in Israel through numerous discussions over many years has contributed valuable insight on water reclamation and reuse; Professor Edward D. Schroeder of the University of California, Davis reviewed an early draft of Chapters 1 and 2; Dr. David York of Florida Department of Environmental Protection reviewed portions of Chapter 2. The collective efforts of these individuals were invaluable and greatly appreciated.

The assistance of the staff of Metcalf & Eddy in preparation of this textbook 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. Sadly, Mr. Anderson never saw the published version of this textbook; he passed away as the manuscript was nearing completion. It was his vision that water reclamation and reuse would become an important part of global water resources management. As Metcalf & Eddy's full time author, Dr. Ryujiro Tsuchihashi with Ms. Kathleen Esposito took on the additional responsibility for the completion of this textbook, Ms. Dorothy Frohlich provided liaison between the authors and reviewers.

Members of the McGraw-Hill staff were also critical to the production of this textbook. Mr. Larry Hager was instrumental in the development of this textbook project. Mr. David Fogarty served as editing supervisor and helped keep all of the loose ends together. Ms. Pamela Pelton served as the production supervisor. Ms. Arushi Chawla served as project manager at International Typesetting and Composition.

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