

Manual of Water Supply Practices

M62

Membrane Applications for Water Reuse

First Edition



American Water Works
Association

Membrane Applications for Water Reuse

First Edition



American Water Works
Association

Membrane Applications for Water Reuse

Copyright © 2018 American Water Works Association

All rights reserved. No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopy, recording, or any information or retrieval system, except in the form of brief excerpts or quotations for review purposes, without the written permission of the publisher.

Disclaimer

The authors, contributors, editors, and publisher do not assume responsibility for the validity of the content or any consequences of its use. In no event will AWWA be liable for direct, indirect, special, incidental, or consequential damages arising out of the use of information presented in this book. In particular, AWWA will not be responsible for any costs, including, but not limited to, those incurred as a result of lost revenue. In no event shall AWWA's liability exceed the amount paid for the purchase of this book.

If you find errors in this manual, please email books@awwa.org. Possible errata will be posted at www.awwa.org/resources-tools/resource.development.groups/manuals-program.aspx.

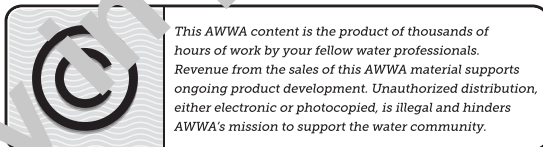
Senior Managing Editor/Project Manager: Melissa Valentine
Cover art: Melanie Yamamoto
Production: Janice Benight
Manuals Specialist: Sue Bach

Library of Congress Cataloging-in-Publication Data

Names: Wong, Joseph, active 2018, author. | Alspach, Brent, author.
Chalmers, Bruce, author. | American Water Works Association, issuing body.
Title: M62 - Membrane applications for water reuse / by Joseph Wong, Brent Alspach, Bruce Chalmers.
Other titles: Membrane applications for water reuse
Description: First edition. | Denver, CO : American Water Works Association, [2018]
Identifiers: LCCN 2018008413 | ISBN 9781625762627
Subjects: LCSH: Water reuse. | Membranes (Technology)
Classification: LCC TD429 .W66 2018 | DDC 63.1/64--dc23
LC record available at <https://lccn.loc.gov/2018008413>

Printed in the United States of America

ISBN 978-1-62576-262-7 eISBN-13 978-1-61300-448-7



**American Water Works
Association**

American Water Works Association
6666 West Quincy Avenue
Denver, CO 80235-3098
awwa.org

Contents

Figures, ix

Tables, xiii

Acknowledgments, xvii

Preface, xxi

Abbreviations, xxiii

Chapter 1	Development of Water Reuse Practices	1
	History of Water Reuse, 1	
	Terminology, 1	
	Unplanned Water Reuse, 2	
	Planned Water Reuse, 2	
	The Role of Membranes in Water Reuse, 3	
	How to Use This Manual, 4	
	References, 6	
Chapter 2	Planning for Reuse Applications	7
	Reuse Applications, 7	
	Nonpotable Reuse, 7	
	Potable Reuse, 9	
	Treatment Options for Water Reuse, 10	
	Effectiveness of Treatment, 11	
	Residuals, Disposal, and Regulatory Requirements, 11	
	Flow Equalization and Storage Requirements for Nonpotable Reuse, 14	
	Environmental Impacts, 14	
	Legal and Institutional Issues, 15	
	Regulatory Requirements and Permitting, Including Future Regulatory Impacts, 15	
	Public Education and Outreach Programs, 15	
	References, 16	
Chapter 3	Water Reuse Guidelines and Regulations	17
	World Health Organization Guidelines, 17	
	National Guidelines, 20	
	Reuse Requirements, 43	
	Guidelines for Other Countries, 45	
	References, 48	
Chapter 4	Source and Treated Water Quality	51
	Wastewater Treatment, 51	
	Wastewater Effluent Quality, 52	
	Specific Wastewater Quality Parameters, 53	
	Industrial Reuse, 57	
	Agricultural Reuse, 60	
	Water Supply Augmentation, 61	
	Augmentation of Indirect Potable Supplies, 62	
	Direct Potable Reuse, 63	

	Water Quality Treatment Requirements, 63	
	References, 66	
Chapter 5	Membrane Process Treatment Facility Design	69
	Pretreatment or Feedwater Conditioning for Membrane Treatment	
	Processes, 69	
	Screening for Removal of Debris and Large Solids, 72	
	Removal of Chemicals Incompatible with Membrane Materials, 74	
	Foulant, Suspended Solids, and Particulates Removal, 76	
	Coagulation–Flocculation, 77	
	Clarification, 78	
	Dissolved Air Flotation, 78	
	Media Filtration, 79	
	Microfiltration–Ultrafiltration as PreTreatment, 80	
	Other Pretreatment Processes for Suspended Solids Removal, 80	
	Controlling Temperature, 80	
	pH, 80	
	Dissolved Ionic Species that Require Preconditioning, 80	
	Oxidation and Reduction Processes, 81	
	Softening, 81	
	Degasser, 83	
	Controlling Biological Fouling, 84	
	Chlorination, 85	
	Micellar-Enhanced Membrane Separation, 86	
	Optimization of Upstream Biological Wastewater Treatment, 87	
	MF–UF Design Considerations, 88	
	MF/UF Design Considerations, 89	
	MF–UF Filtrate Quality Requirements, 89	
	MF–UF Filtrate Quality Requirements for Water Reuse, 90	
	Impact of Feedwater Quality on Pretreatment and MF–UF System	
	Design, 91	
	MF–UF Equipment, 93	
	Reverse Osmosis–Microfiltration, 95	
	Impact of Feedwater Quality on Pretreatment and NF–RO System	
	Design, 97	
	Post-Treatment, Stabilization, and Disinfection, 111	
	Stabilization, 112	
	Treatment Requirements, 114	
	Treatment Processes, 115	
	Advanced Oxidation Systems, 117	
	Design Considerations, 121	
	Water Quality Impacts, 121	
	References, 122	
Chapter 6	Operations	125
	Membrane System Data Collection and Analysis, 125	
	Operating Data, 127	
	Membrane Integrity Test, 129	
	Heterotrophic Plate Count, 131	
	Operational Considerations, 131	
	Membrane Cleaning and Flux Recovery, 135	
	Integrity Testing, 141	
	Membrane Storage, 143	

	Membrane Replacement, 143	
	New Membrane Procurement, 144	
	Maintenance, 145	
	Troubleshooting, 145	
Chapter 7	Residuals Management	149
	Residuals Management for Low-Pressure Membranes, 150	
	Residuals Management Techniques, 150	
	Concentrate Management for High-Pressure Membranes, 152	
	Issues Related to Concentrate Disposal, 153	
	Health and Environmental Issues, 154	
	Cost and Energy Issues, 154	
	Concentrate Disposal Options, 155	
	Current Research, 164	
	Regulatory Issues, 165	
	References, 169	
Chapter 8	Cost of Treatment	173
	Summarizing Project Costs, 173	
	Development of Construction Cost Model, 175	
	Contributing Factors to Capital Costs, 175	
	Development of an O&M Cost Model, 180	
	Cost of Water, 184	
	Example Cost Estimates, 185	
	References, 187	
Chapter 9	Case Studies	189
	Case Study: The Groundwater Replenishment System, 189	
	Project Photos, 194	
	Case Study: Broad Run Water Reclamation Facility, 197	
	Plant Description, 198	
	Membrane System Design Summary, 198	
	Plant Costs, 199	
	Conclusions, 200	
	Project Photos, 200	
	Case Study: Big Spring Raw Water Production Facility – Colorado River Municipal Water District, 202	
	Plant Description, 202	
	Reverse Osmosis Feedwater Pretreatment, 203	
	Water Quality, 204	
	Plant Costs, 204	
	Project Photos, 205	
	Case Study: Edward C. Little Water Recycling Facility, 206	
	Plant Description, 207	
	Treated Water Quality Produced, 210	
	Capital Costs, 211	
	Operation and Maintenance Costs, 211	
	Case Study: Singapore NEWater Facilities, 211	
	Singapore's First Initiative on Recycling: Industrial Water, 211	
	The NEWater Study, 212	
	Public Education, 213	
	Full-Scale Implementation of NEWater, 213	
	Project Photos, 215	

	Case Study: Bundamba 1A Advanced Water Reclamation Facility – Southeast Queensland Water, 218
	Water Quality, 219
	Operational Performance, 222
	Case Study: Gibson Island Advanced Water Treatment Plant – South East Queensland Water, 225
	Plant Description, 225
	Capital Costs, 227
	Conclusion, 228
	Project Photos, 228
	References, 230
	Case Study: Luggage Point Advanced Water Treatment Plant – Southeast Queensland Water, 231
	Influent Characteristics and Treated Water Quality Requirements, 231
	Treatment Process, 231
	Plant Performance Relative to Treated Water Requirements, 238
	Costs, 238
	Summary, 238
	References, 238
	Case Study: CAPCO Industrial Wastewater Reclamation Facility, 239
	Wastewater Reclamation System Description, 240
	Economic Analysis for the Reuse Project, 240
	Full-scale Implementation, 243
	A Brief Review of the 13 Years of Operation, 243
	References, 245
Chapter 10	Future Technology Trends and Contaminants of Emerging Concern....247
	Advances in Low-Pressure Membranes, 247
	Ceramic Membranes, 248
	Universal MF–UF Membrane Slud, 249
	Advances in Reverse Osmosis Membrane Cleaning, 249
	New Membrane Materials for Desalination, 251
	Novel Membrane Processes for Desalination, 254
	Contaminants of Emerging Concern, 257
	References, 267
Appendix A	The Groundwater Replenishment System Design Criteria and Water Quality Tables, 275
Appendix B	Brook Run Water Reclamation Facility Design Criteria and Water Quality Tables, 279
Appendix C	Big Spring Raw Water Production Facility Design Criteria and Water Quality Tables, 281
Appendix D	Edward C. Little Water Recycling Facility Design Criteria and Water Quality Tables, 283
Appendix E	Singapore NEWater Facilities Process Design Criteria and Water Quality Tables, 289

**Appendix F Western Corridor Water Recycling Scheme Design Criteria and
Water Quality Tables, 295**

**Appendix G CAPCO Industrial Wastewater Reclamation Facility Design Criteria
and Water Quality Tables, 307**

Index, 309

AWWA Manuals, 319

Currently in preview, click buy full version

Figures

- 2-1 Summary of water reuse applications in the United States, 8
- 4-1 Treatment technologies to achieve desired levels of reclaimed water quality, 52
- 5-1 Water reuse membrane treatment hierarchy, 70
- 5-2 Typical automatic backwashing screen used in microfiltration–ultrafiltration systems, 73
- 5-3 Automatic backwashing disc (left) and wound microfiber cassette filters (right), 74
- 5-4 Hillsboro Beach, Fla., pellet lime softener installation, 82
- 5-5 Integrated precipitative membrane treatment, 83
- 5-6 Ultrafiltration membrane surface showing pores, 88
- 5-7 Microfiltration–ultrafiltration filtration modes, 89
- 5-8 Principle of reverse osmosis, 96
- 5-9 Rejection capabilities of various membranes and required operating pressure, 97
- 5-10 Scanning electron microscope image of a fouled membrane used to treat secondary effluent. Severe fouling by calcium aluminum silicates is seen, 101
- 5-11 Microfiltration (foreground) and reverse osmosis (RO; background) installation at the Bundamba advanced water reclamation plant in Australia. The RO membranes are 18 in. in diameter, 105
- 5-12 Reverse osmosis trains at Changi North Water Facility, Singapore, 107
- 5-13 A three-stage reverse osmosis train, 108
- 5-14 Energy-recovery device in a reverse osmosis system that recovers the energy in the concentrate and reuses it to boost the second-stage feed pressure, 109
- 5-15 Flows and pressures through each stage of a reverse osmosis train, with and without an energy recovery device, 109
- 5-16 Liqui-cel membrane contactor, 116
- 5-17 Clearwater, Fla., groundwater replenishment process flow diagram, 118
- 6-1 Illustration of the importance of maintaining sufficient start pressures for a membrane integrity test, 129
- 6-2 Particulate and debris collected within the cartridge filter housing (left) and on the cartridge filters (right), 134
- 6-3 Scanning electron microscopy images of a clean reverse osmosis membrane surface (left) and one containing silicate scale (right), 135
- 6-4 Changing reverse osmosis system performance parameters in response to a membrane fouling event, 136
- 6-5 Ratio of specific flux at the tail-end stage to the total system specific flux. Note the declining ratio while the overall system specific flux remains unchanged, 136
- 6-6 Scanning electron microscopy images of a membrane hollow fiber (left) and accumulated foulant on the outside fiber surface (right), 137

- 6-7 Example of transmembrane pressure increases versus time for consecutive cleaning intervals. Note the baseline, declining, and restoration of membrane permeability are reflective of potential irreversible fouling or chemical cleaning effectiveness, 139
- 6-8 Restoration of reverse osmosis membrane flux to initial baseline permeability after chemical cleaning, 141
- 7-1 Mechanical vapor compression brine concentrator, 163
- 7-2 Mechanical vapor compression crystallizer, 163
- 8-1 Nonpotable reuse treatment plant construction cost for a microfiltration-based facility, 176
- 8-2 Potable reuse treatment plant construction cost for a microfiltration–reverse osmosis–based facility, 177
- 8-3 Typical nonpotable reuse treatment plant operations and maintenance cost breakdown for a microfiltration-based facility, 181
- 8-4 Typical potable reuse treatment plant operations and maintenance cost breakdown for a microfiltration–reverse osmosis–based facility, 181
- 8-5 Nonpotable reuse treatment plant cost of water for a microfiltration-based facility, 184
- 8-6 Potable reuse treatment plant cost of water for a microfiltration–reverse osmosis–based facility, 185
- 9-1 Groundwater Replenishment System components, 190
- 9-2 Groundwater Replenishment System process flow diagram and sampling points, 191
- 9-3 Aerial view of the Groundwater Replenishment System and adjacent Orange County Sanitation District facility, 194
- 9-4 Groundwater Replenishment System facility entrance, 195
- 9-5 Microfiltration system, 195
- 9-6 Reverse osmosis treatment trains, 196
- 9-7 Ultraviolet light–advanced oxidation process treatment facility, 196
- 9-8 Process schematic for the Broad Run Water Reclamation Facility, 198
- 9-9 Membrane bioreactor tanks and pipework, 200
- 9-10 Granular activated carbon contactors and pipework, 201
- 9-11 Ultraviolet light reactors, 201
- 9-12 Process schematic for the Colorado River Municipal Water District raw water production facility in Big Spring, Texas, 203
- 9-13 Microfiltration system, 205
- 9-14 Reverse osmosis system, 205
- 9-15 Process schematic of the Edward C. Little Water Recycling Facility, 208
- 9-16 Ozone injection system, 209
- 9-17 Phase III CMF units, 209
- 9-18 Flow schematic of NEWater factories, 214
- 9-19 Zeeweed ultrafiltration at Bedok NEWater Factory, phase 1, 215
- 9-20 Microza microfiltration at Bedok NEWater Factory, phase 2, 215

- 9-21 Large-diameter (16-in.) reverse osmosis trains at Bedok NEWater Factory, phase 2, 216
- 9-22 Memcor CMF-S system at Kranji NEWater Factory, phases 1 and 2, 216
- 9-23 Reverse osmosis units at Kranji NEWater Factory, phases 1 and 2, 217
- 9-24 Process flow diagram for Bundamba advanced wastewater treatment plant, 220
- 9-25 Microfiltration unit 2 operating performance at the Bundamba advanced wastewater treatment plant, 222
- 9-26 Permeability trends for reverse osmosis units at the Bundamba advanced wastewater treatment plant, 223
- 9-27 Energy consumption at the Bundamba advanced wastewater treatment plant, 224
- 9-28 Gibson Island advanced wastewater treatment process schematic, 225
- 9-29 Gibson Island advanced wastewater treatment plant ultrafiltration unit, 228
- 9-30 Gibson Island advanced wastewater treatment plant reverse osmosis unit, 229
- 9-31 Gibson Island advanced wastewater treatment plant. In the foreground are ultraviolet units, on the left are ultrafiltration units, and in the back are reverse osmosis units, 229
- 9-32 Process flow diagram for the Luggage Point advanced water treatment plant, 232
- 9-33 Pall Microza microfiltration racks, 234
- 9-34 Beneficial impact of fouling management modifications on microfiltration permeability, 234
- 9-35 Three-stage reverse osmosis skid. The hydraulic turbocharger is shown on bottom left, 235
- 9-36 Normalized permeate flow for the Luggage Point advanced water treatment plant reverse osmosis train 1 from start-up to Sept. 3, 2010, 236
- 9-37 Normalized salt passage for the Luggage Point advanced water treatment plant reverse osmosis train 1 from start-up to Sept. 3, 2010, 236
- 9-38 Normalized differential pressure for the Luggage Point advanced water treatment plant reverse osmosis train 1 from start-up to Sept. 3, 2010, 237
- 9-39 One of the four Trojan ultraviolet PHOX units, 237
- 9-40 Relation of wastewater reclamation system with plant water systems, 241
- 9-41 Wastewater recovery treatment system block flow diagram, 241
- 9-42 Conductivity of reverse osmosis feed and combined permeate from all trains from April 2001 to March 2003, 244

- 10-1 Categories of constituents of emerging concern by chemical characteristics, 261
- 10-2 Rejection diagram for organic micropollutants during membrane treatment, 265

Tables

- 1-1 Selected worldwide indirect and direct potable reuse facilities, 3
- 2-1 Indicative log removals for various stages of treatment and unit processes, 12
- 2-2 Filter pore size comparison, 13
- 3-1 Health-based targets and helminth reduction targets for wastewater use in agriculture, 18
- 3-2 Maximum tolerable soil concentrations of various toxic chemicals based on human health protection, 19
- 3-3 Recommended minimum verification monitoring for wastewater and excreta use in agriculture and aquaculture, 21
- 3-4 Victoria, Australia, reclaimed water classes, treatment, and pathogen reduction, 22
- 3-5 New South Wales, Australia, guidelines for reclaimed water use from municipal sewage treatment plants, 23
- 3-6 Japan's water reuse standards, 25
- 3-7 Suggested guidelines for water reuse, 26
- 3-8 Arizona water reuse types and classes, 36
- 3-9 California water reuse types and classes, 37
- 3-10 Florida water reuse types described in Florida Administrative Code 62-610, 41
- 3-11 Nevada water reuse types and classes, 42
- 3-12 Texas water reuse types and classes, 43
- 3-13 Washington water reuse types and classes, 44
- 3-14 Links to water reuse regulations, guidance, and fact sheets, 44
- 3-15 British microbial guidelines for graywater systems, 46
- 3-16 Singapore water quality standards, 2012, 47
- 3-17 Windhoek direct potable reuse water quality criteria, 47
- 4-1 Typical ranges of municipal wastewater and secondary treatment effluent quality, 53
- 4-2 Water quality parameters and their impact on membranes for water reuse applications, 54
- 4-3 Typical membrane product water quality for low- and high-pressure membranes, 56
- 4-4 Typical cycles of concentration, 58
- 4-5 Typical reclaimed water quality requirements for various industrial processes, 60
- 4-6 Typical reclaimed water quality requirements for various industrial processes, 61
- 4-7 Unit processes used for the removal of classes of constituents found in wastewater for reuse applications, 64

- 4-8 Typical product water quality for reverse osmosis membranes, 65
- 5-1 Filtration media pores sizes, 71
- 5-2 Polymeric membrane materials, 74
- 5-3 Typical microfiltration–ultrafiltration design criteria for water reuse facilities, 91
- 5-4 Example large-capacity water reuse projects that use microfiltration–ultrafiltration, 94
- 5-5 Monitoring methods for microfiltration–ultrafiltration systems, 95
- 5-6 Values of calcium carbonate precipitation potential, 113
- 5-7 Removal of microconstituents by ultraviolet (UV) irradiation, UV irradiation/hydrogen peroxide, and ozone, 120
- 6-1 General reverse osmosis data collection, 130
- 6-2 General reverse osmosis cleaning chemical guidelines, 140
- 7-1 Summary of coagulation–flocculation–sedimentation processes, 151
- 7-2 Microfiltration–ultrafiltration residuals and applicable regulations, 167
- 8-1 Membrane-based reuse treatment plant capital cost examples, with plant capacity of 10 mgd, 186
- 8-2 Membrane-based reuse treatment plant operations and maintenance cost examples, with plant capacity of 10 mgd, 186
- 8-3 Membrane-based reuse treatment plant cost of water, with plant capacity of 10 mgd, 187
- 9-1 Groundwater replenishment system capital cost breakdown, 193
- 9-2 Groundwater replenishment system operating costs, 194
- 9-3 Permit requirements for the Broad Run Water Reclamation Facility, 197
- 9-4 Cost information for NEWater factories, 218
- 9-5 Reverse osmosis performance at Bumdamba stage 1A, 223
- 9-6 Gibson Island advanced wastewater treatment plant log-removal values, 227
- 9-7 Gibson Island advanced wastewater treatment plant costs, 228
- 9-8 *N*-nitrosodimethylamine levels prior to and following preformed chloramination, 233
- 9-9 Estimated capital cost of the wastewater reclamation system: 3.0 mgd of product water, 1998, 242
- 9-10 Estimated annual operations and maintenance cost of the wastewater reclamation system: 3.0 mgd of product water, 1998, 242
- 9-11 Project cost analysis of the wastewater reclamation system: 3.0 mgd of product water, 1998, 243
- 10-1 Pharmaceutically active compounds and rank of use, 259
- 10-2 Commonly used personal care products, 259
- 10-3 Pesticides, herbicides, and insecticides found in water and wastewater, 259
- 10-4 Observed average efficiencies of membrane bioreactors in the removal of various constituents of emerging concern, 263

- 10-5 Predictions of removal of constituents of emerging concern by nanofiltration and reverse osmosis, 264
- 10-6 Efficiencies of nanofiltration and reverse osmosis in the removal of various constituents of emerging concern, 266

- A-1 MF system key design parameters, 275
- A-2 RO system key design parameters, 275
- A-3 GWRS typical water quality, 276

- B-1 Design summary—Broad Run WRF Membrane Bioreactor System, 279
- B-2 Broad Run Water Reclamation Facility—influent and effluent characteristics, 280

- C-1 Membrane system design criteria, 281
- C-2 Feed water quality (July 2008–March 2013), 282

- D-1 Feed water quality, 283
- D-2 Ozone system design criteria, 283
- D-3 Microfiltration design criteria, 284
- D-4 Reverse osmosis design criteria, 284
- D-5 Advanced oxidation process, 285
- D-6 Barrier recycled water constituents (2012), 285
- D-7 Single pass low pressure boiler feed water, 287
- D-8 Double pass high pressure boiler feed water, 287

- E-1 Design characteristics of treatment processes used at NEWater Demonstration Plant, 289
- E-2 Feedwater characteristics of Bedok NEWater Demonstration Plant, 289
- E-3 Design criteria for plant processes and equipment at Bedok NEWater factory, 290
- E-4 Design criteria for plant processes and equipment at Kranji NEWater factory, 291
- E-5 Details of plant processes and equipment at Ulu Pandan & Changi NEWater factories, 292
- E-6 Treated water quality criteria for NEWater treatment processes, 293
- E-7 Typical NEWater quality, 294

- F-1 Raw water quality for Bundamba Advanced Water Reclamation Facility, 295
- F-2 Treated water quality requirements for Bundamba Advanced Water Reclamation Facility (selected parameters, in addition to Australian Drinking Water Guidelines), 296
- F-3 Concentrate water quality requirements for Bundamba AWTF 1A, 297
- F-4 MF design criteria and performance at Bundamba AWTF, 297
- F-5 Gibson Island AWTP feed water design basis, 297
- F-6 Gibson Island AWTP treated water quality requirements, 298
- F-7 Gibson Island AWTP UF system design criteria, 298
- F-8 Gibson Island AWTP RO system design criteria, 299

- F-9 Gibson Island AWTP treated water quality requirements (ADWG and owner) and typical values, 299
- F-10 Gibson Island AWTP performance vs. reclaimed water requirements, 300
- F-11 Luggage Point AWTP influent (feed water) quality design basis (selected parameters), 303
- F-12 Luggage Point AWTP treated water quality requirements (supplement to ADWG), 304
- F-13 Luggage Point AWTP MF system design criteria, 304
- F-14 Luggage Point AWTP RO system design criteria, 305
- F-15 Luggage Point AWTP treated water quality: requirements versus plant performance test, 305

- G-1 Wastewater effluent characteristics and discharge requirements, 307
- G-2 Effluent water quality, 308

Acknowledgments

The AWWA Technical and Educational Council, the Water Quality and Technology Division, and the Membrane Processes committee gratefully acknowledge the contributions of the volunteers who drafted, edited, and provided the significant and critical commentary essential to the development of AWWA M62. The Technical Review Board members dedicated many hours in the final stages of preparation of this edition to ensure the overall technical quality, consistency, and accuracy of the manual.

Technical Review Board Members

Joseph Wong, Chair, Brown and Caldwell, Walnut Creek, Calif.
Brent Alspach, ARCADIS, Carlsbad, Calif.
Bruce Chalmers, CDM Smith, Irvine, Calif.
Dawn Flancher, AWWA Staff, Denver, Colo.
Judith Herschell, Herschell Environment, Pittsburgh, Penn.
Kenneth Mercer, AWWA Staff, Denver, Colo.

Authors of the First edition

*A special thank you to these volunteers who served as chapter coordinators.

Joseph Wong,* Chair, Brown and Caldwell, Walnut Creek, Calif.
Jorge Aguinaldo,* RWL Water, Tampa, Fla.
Rick Bond, Black & Veatch, Kansas City, Mo.
Thomas Broderick, Loudoun Water, Ashburn, Vir.
Charlie Cruz, Separation Processes Inc., Carlsbad, Calif.
Emily Davis, Separation Processes Inc., Carlsbad, Calif.
James (Jay) DeCarolis, Black & Veatch, San Marcos, Calif.
Andrew Findlay, MWH Australia, Manly West, Qld Australia
Val Frenkel, EKI, Erler & Kalinowski Inc., Burlingame, Calif.
Silvana M. Ghiu,* Hazen and Sawyer, San Diego, Calif.
Wesley Harijanto, California State Polytechnic University, Pomona, Calif.
Turaj Hosseini, Separation Processes Inc., Carlsbad, Calif.
Gary L. Hunter, Black & Veatch, Kansas City, Mo.
Curtis Kiefer, CDM Smith, Fort Lauderdale, Fla.
Tom Knoell, Orange County Water District, Fountain Valley, Calif.
Edmund A. Kobylinski, Black & Veatch, Cary, N.C.
Natalie W. La, California State Polytechnic University, Pomona, Calif.
Jim Lozier,* ch2m, Tempe, Ariz.
Robert McCandless, Brown and Caldwell, Phoenix, Ariz.
Chandra Mysore,* JACOBS™, Atlanta, Ga.
Jeff Neemann, Black & Veatch Corp., Kansas City, Mo.

Key Wee Ong, Singapore Public Utilities Board, Singapore
Eric Owens, West Basin Municipal Water District, Carson, Calif.
Mehul Patel, Orange County Water District, Fountain Valley, Calif.
Alan E. Rimer, Black & Veatch, Cary, N.C.
Cheryl Ross, West Basin Municipal Water District, Long Beach, Calif.
Larry Schimmoller, ch2m, Englewood, Colo.
Rich Stratton, HDR, Shingle Springs, Calif.
Arun Subramani, MWH, Arcadia, Calif.
Jennifer Thompson, CDM Smith, Carlsbad, Calif.
Ralph Valencia, United Water, Los Angeles, Calif.
Don Vandertulip,* Arcadis, Dallas, Texas
Vasu Veerapaneni,* Black & Veatch, Kansas City, Mo.
Alex Wesner, Separation Processes Inc., Carlsbad, Calif.
Greg Wetterau,* CDM Smith, Rancho Cucamonga, Calif.
Wyatt Won, West Basin Municipal Water District, Carson, Calif.
Joe Zhao, URS Corporation, Santa Ana, Calif.
Christine Zheng, California State Polytechnic University, Pomona, Calif.

Reviewers to the First Edition

Robert Bergman, ch2m, Gainesville, Fla.
James Crook, Environmental Consultant, Norwell, Mass.

Chapter Authors

Chapter 1: Development of Water Reuse Practices

Don Vandertulip and Val Frenkel

Chapter 2: Planning for Reuse Applications

Don Vandertulip and Lisa Prieto

Chapter 3: Water Reuse Guidelines and Regulations

Joseph Wong and Cheryl Ross

Chapter 4: Source and Treated Water Quality

Chandra Mysore and Joseph Zhao

Chapter 5: Membrane Process Treatment Facility Design

*Jorge T. Aguinaldo, James De Carolis, Srinivas Veerapaneni, Scott Freeman,
Alex Wesner, Robert Bergman, Jeff Neemann, and James Lozier*

Chapter 6: Operations

*Silvana Ghiu, Eric Owens, Emily Davis, Turaj Hosseini,
Ralph Valencia, Tom Knoell, and Wyatt Won*

Chapter 7: Residuals Management

Chandra Mysore, Rick Bond, and Edmund Kobylinski

Chapter 8: Cost of Treatment

Greg Wetterau and Curt Kiefer

Chapter 9: Case Studies

Authors are listed in each case study

Chapter 10: Future Technology Trends and Contaminants of Emerging Concerns

Joseph Wong, Arun Subramani, and Robert McCandless

Preface



Reverse osmosis (RO) membranes have been used in water reuse since the 1960s. Cellulose acetate membranes for treating conventionally clarified municipal effluent was initially applied to small industrial applications and as irrigation water for golf courses. In the 1970s, Orange County Water District in southern California used cellulose acetate membranes to produce 5 mgd of RO permeate that was blended with imported water for injection into seawater intrusion barrier wells. The use of membranes in full-scale reuse applications has changed dramatically based on research performed in the 1980s and 1990s. Those efforts demonstrated that microfiltration–ultrafiltration (MF–UF) membranes can offer superior pretreatment compared to RO when treating municipal effluents. Those efforts also incorporated polyamide membrane, which has all but replaced cellulose acetate in this application.

In the 1990s, many municipal agencies began operating full-scale MF–UF and polyamide RO membrane systems to treat secondary and tertiary municipal effluents. At that time, early adopters of large-scale membrane treatment processes for water reuse were rare. These membrane users transitioned the industry from theoretical and pilot-scale investigations into full-scale operations, bringing about a new facet of water reuse. In the years since, the industry has learned much about membrane performance and sustainability over long-term operation, including handling unanticipated operational challenges brought on by organic-laden, variable feed sources that can change not only year to year but sometimes day to day.

Operational considerations for low- and high-pressure membrane technologies in water reuse applications are similar to their potable system analogs. However, there are subtle differences that can pose additional problems or issues to the water reuse operator if these are not considered or anticipated. Membrane system operators in reuse applications need to understand that “industry guidance” has historically been based on potable water treatment applications. Irreversible fouling and flux loss that lead to increased cleaning intervals and reduced membrane life are constant challenges in this environment. Finding the balance between cleaning frequency and chemical and energy costs is often the goal for membrane facilities in water reuse applications. Fiber breakage and loss of RO membrane rejection are significant problems that can be accelerated by this source water. This manual presents a comprehensive description of the issues related to applying membrane technologies in water reuse projects.

Abbreviations

ACH	aluminum chlorohydrate
ANL	Argonne National Laboratory
ANSI	American National Standards Institute
AOC	assimilable organic carbon
AOP	advanced oxidation process
ASR	aquifer storage and recovery
AWT	advanced water treatment
AWWA	American Water Works Association
BAC	biologically active carbon
BIRM	biological immune response modulator
BNR	biological nutrient removal
BOD	biological oxygen demand
CA	cellulose acetate
Ca(OCl) ₂	calcium hypochlorite
CEC	chemicals of emerging concern
CIP	clean in place
COC	cycles of concentration
COD	chemical oxygen demand
CTA	cellulose triacetate
DAF	dissolved air flotation
DALY	disability-adjusted life year
DOE	Department of Energy
DPR	direct potable reuse
EC	electrical conductivity
ED	electrodialysis
ED–EDR	electrodialysis–electrodialysis reversal
EDC	endocrine-disrupting chemical
EDR	electrodialysis reversal
efOM	effluent organic matter
ESA	Endangered Species Act
FAC	free available chlorine
FeCl ₃	ferric chloride
GRRP	groundwater recharge reuse projects
GWI	Global Water Intelligence
GWRRDR	Groundwater Replenishment Reuse Draft Regulation
HPM	high-pressure membrane
IMS	integrated membrane system

IPR	indirect potable reuse
LPM	low-pressure membrane
LRV	log-reduction value
MBR	membrane bioreactor
MCL	maximum contaminant limit
MF	microfiltration
MFI	modified fouling index
MGD	million gallons per day
MIC	microbiologically induced corrosion
MMFI	mini-plugging factor index
NaOCl	sodium hypochlorite
NDMA	<i>N</i> -nitrosodimethylamine
NF	nanofiltration
NOM	natural organic matter
NPDES	National Pollutant Discharge Elimination System
NTU	nephelometric turbidity unit
NWRI	National Water Research Institute
O&M	operations and maintenance
PA	polyamide
PAC	powdered activated carbon
PACl	polyaluminum chloride
PES	polyether sulfone
PP	polypropylene
PPCP	pharmaceuticals and personal care products
ppm	parts per million
PSU	polysulfone
PVDF	polyvinyl fluoride
RIB	rapid infiltration basins
RO	reverse osmosis
RWC	recycled water contribution
RWQCB	regional water quality control board
SAR	soil adsorption ratio
SAT	soil aquifer treatment
SBS	sodium bisulfite
SDI	silt density index
SMP	soluble microbial products
TCEQ	Texas Commission on Environmental Quality
TDC	total direct cell
TDS	total dissolved solids

TKN	total Kjeldahl nitrogen
TMDL	total maximum daily load
TOC	total organic carbon
TSS	total suspended solids
UF	ultrafiltration
USEPA	US Environmental Protection Agency
VOC	volatile organic compound
WHO	World Health Organization
WRA	WaterReuse Association
WTP	water treatment plant
WWTP	wastewater treatment plant

Development of Water Reuse Practices

HISTORY OF WATER REUSE

Reuse of water has occurred for centuries beginning with reuse of liquid waste in agricultural practice. Sewage farming was practiced in the United States in the 1800s and peaked in California in 1923, with 70 communities applying their municipal wastewater directly on food crops (NRC 2012). Agricultural water reuse was prominent in Texas south of San Antonio starting in the 1880s, with a formal contract between the City of San Antonio and the San Antonio Irrigation Company in 1901. Other Texas cities followed—Amarillo in 1920, Lubbock in 1930, Odessa in 1940, and Abilene in 1960—providing reclaimed water to farmers and ranchers. As cities grew, centralized wastewater treatment was more widely used and improved water quality, allowing for the first small urban water reuse system for irrigation of Golden Gate Park in San Francisco in 1912 (WRA 2012).

Industrial reuse of water reclaimed from treated municipal wastewater was documented in the 1940s, with the city of Big Spring, Texas, supplying the Cosden Oil and Chemical refinery in 1944. The cities of Odessa and Amarillo followed in the 1950s and the 1960s; this was the beginning of reclaimed water use for power plant cooling in several Texas cities (Texas Water Development Board 2011). In the early 1970s, Bethlehem Steel in Baltimore, Md., began using 100 mgd of reclaimed water for industrial purposes (USEPA 2004). By 2010, 57 power plants in 16 states were using reclaimed water for power plant cooling (DOE-ANL 2007).

TERMINOLOGY

ANSI/AWWA G481 (2014), *Reclaimed Water Program for Operation and Management*, describes the critical requirements for effective operation and management of a reclaimed water program and defines reclaimed water as water recovered following treatment of domestic