3rd edition

Principles of Environmental Engineering and Science

Mackenzie L. Davis and Susan J. Masten

Principles of Environmental Engineering and Science

Third Edition

Mackenzie L. Davis
Emeritus, Michigan State University—East Lansing

Susan J. Masten
Michigan State University—East Lansing, MI

Mc
Graw
Hill
Connect
Learn
Succeed™

The McGraw-Hill Companies

Mc Graw Hill
Connect
Learn
Succeed™

PRINCIPLES OF ENVIRONMENTAL ENGINEERING AND SCIENCE, THIRD EDITION

Published by McGraw-Hill, a business unit of The McGraw-Hill Companies, Inc., 1221 Avenue of the Americas, New York, NY 10020.

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 0 RJE/RJE 1 0 9 8 7 6 5 4 3 2

ISBN 978-0-07-339790-0
MHID 0-07-339790-3

Senior Vice President, Products & Markets: *Kurt L. Strand*
Vice President, General Manager: *Marty Lange*
Vice President, Content Production & Technology Services: *Kimberly Meriwether David*
Managing Director: *Michael D. Lange*
Marketing Manager: *Curt Reynolds*
Development Editor: *Lorraine Buczek*
Project Manager: *Mary Jane Lampe*
Cover Designer: *Studio Montage, St. Louis, MO*
Cover Image: *All cover images courtesy of Susan Masten and Rebecca Masten-Davies*
Buyer: *Jennifer Pickel*
Media Project Manager: *Prashanthi Nadipalli*
Compositor: *MPS Limited*
Typeface: *10/12 Times*
Printer: *R. R. Donnelley*

All credits appearing on page or at the end of the book are considered to be an extension of the copyright page.

Library of Congress Cataloging-in-Publication Data

Davis, Mackenzie Leo, 1941-
Principles of environmental engineering and science / Mackenzie L. Davis, Susan J. Masten.— Third edition.
pages cm.— (Principles of environmental engineering and science)
ISBN 978-0-07-339790-0 (alk. paper)
1. Environmental engineering. 2. Environmental sciences. I. Masten, Susan J. II. Title.

TD145.D2623 2014
628—dc23 2012036164

www.mhhe.com

List of the Elements with Their Symbols and Atomic Masses*

Element	Symbol	Atomic Number	Atomic Mass†
Actinium	Ac	89	(227)
Aluminum	Al	13	26.98
Americium	Am	95	(243)
Antimony	Sb	51	121.8
Argon	Ar	18	39.95
Arsenic	As	33	74.92
Astatine	At	85	(210)
Barium	Ba	56	137.3
Berkelium	Bk	97	(247)
Beryllium	Be	4	9.012
Bismuth	Bi	83	209.0
Bohrium	Bh	107	(262)
Boron	B	5	10.81
Bromine	Br	35	79.90
Cadmium	Cd	48	112.4
Calcium	Ca	20	40.08
Californium	Cf	98	(249)
Carbon	C	6	12.01
Cerium	Ce	58	140.1
Cesium	Cs	55	132.9
Chlorine	Cl	17	35.45
Chromium	Cr	24	52.00
Cobalt	Co	27	58.93
Copper	Cu	29	63.55
Curium	Cm	96	(247)
Darmstadtium	Ds	110	(269)
Dubnium	Db	105	(260)
Dysprosium	Dy	66	162.5
Einsteinium	Es	99	(254)
Erbium	Er	68	167.3
Europium	Eu	63	152.0
Fermium	Fm	100	(253)
Fluorine	F	9	19.00
Francium	Fr	87	(223)
Gadolinium	Gd	64	157.3
Gallium	Ga	31	69.72
Germanium	Ge	32	72.59
Gold	Au	79	197.0
Hafnium	Hf	72	178.5
Hassium	Hs	108	(265)
Helium	He	2	4.003
Holmium	Ho	67	164.9
Hydrogen	H	1	1.008
Indium	In	49	114.8
Iodine	I	53	126.9
Iridium	Ir	77	192.2
Iron	Fe	26	55.85
Krypton	Kr	36	83.80
Lanthanum	La	57	138.9
Lawrencium	Lr	103	(257)
Lead	Pb	82	207.2
Lithium	Li	3	6.941
Lutetium	Lu	71	175.0
Magnesium	Mg	12	24.31
Manganese	Mn	25	54.94
Meitnerium	Mt	109	(266)
Mendelevium	Md	101	(256)
Mercury	Hg	80	200.6
Molybdenum	Mo	42	95.94
Neodymium	Nd	60	144.2
Neon	Ne	10	20.18
Neptunium	Np	93	(237)
Nickel	Ni	28	58.69
Niobium	Nb	41	92.91
Nitrogen	N	7	14.01
Nobelium	No	102	(253)
Osmium	Os	76	190.2
Oxygen	O	8	16.00
Palladium	Pd	46	106.4
Phosphorus	P	15	30.97
Platinum	Pt	78	195.1
Plutonium	Pu	94	(242)
Polonium	Po	84	(210)
Potassium	K	19	39.10
Praseodymium	Pr	59	140.9
Promethium	Pm	61	(147)
Protactinium	Pa	91	(231)
Radium	Ra	88	(226)
Radon	Rn	86	(222)
Rhenium	Re	75	186.2
Rhodium	Rh	45	102.9
Roentgenium	Rg	111	(272)
Rubidium	Rb	37	85.47
Ruthenium	Ru	44	101.1
Rutherfordium	Rf	104	(257)
Samarium	Sm	62	150.4
Scandium	Sc	21	44.96
Seaborgium	Sg	106	(263)
Selenium	Se	34	78.96
Silicon	Si	14	28.09
Silver	Ag	47	107.9
Sodium	Na	11	22.99
Strontium	Sr	38	87.62
Sulfur	S	16	32.07
Tantalum	Ta	73	180.9
Technetium	Tc	43	(99)
Tellurium	Te	52	127.6
Terbium	Tb	65	158.9
Thallium	Tl	81	204.4
Thorium	Th	90	232.0
Thulium	Tm	69	168.9
Tin	Sn	50	118.7
Titanium	Ti	22	47.88
Tungsten	W	74	183.9
Uranium	U	92	238.0
Vanadium	V	23	50.94
Xenon	Xe	54	131.3
Ytterbium	Yb	70	173.0
Yttrium	Y	39	88.91
Zinc	Zn	30	65.39
Zirconium	Zr	40	91.22

---

*All atomic masses have four significant figures. These values are recommended by the Committee on Teaching of Chemistry, International Union of Pure and Applied Chemistry.

†Approximate values of atomic masses for radioactive elements are given in parentheses.

9
F
Fluorine
19.00

Atomic number
Atomic mass

1 1A	2 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8	9 8B	10	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
1 **H** Hydrogen 1.008																	2 **He** Helium 4.003
3 **Li** Lithium 6.941	4 **Be** Beryllium 9.012											5 **B** Boron 10.81	6 **C** Carbon 12.01	7 **N** Nitrogen 14.01	8 **O** Oxygen 16.00	9 **F** Fluorine 19.00	10 **Ne** Neon 20.18
11 **Na** Sodium 22.99	12 **Mg** Magnesium 24.31											13 **Al** Aluminum 26.98	14 **Si** Silicon 28.09	15 **P** Phosphorus 30.97	16 **S** Sulfur 32.07	17 **Cl** Chlorine 35.45	18 **Ar** Argon 39.95
19 **K** Potassium 39.10	20 **Ca** Calcium 40.08	21 **Sc** Scandium 44.96	22 **Ti** Titanium 47.88	23 **V** Vanadium 50.94	24 **Cr** Chromium 52.00	25 **Mn** Manganese 54.94	26 **Fe** Iron 55.85	27 **Co** Cobalt 58.93	28 **Ni** Nickel 58.69	29 **Cu** Copper 63.55	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.72	32 **Ge** Germanium 72.59	33 **As** Arsenic 74.92	34 **Se** Selenium 78.96	35 **Br** Bromine 79.90	36 **Kr** Krypton 83.80
37 **Rb** Rubidium 85.47	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.91	40 **Zr** Zirconium 91.22	41 **Nb** Niobium 92.91	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium (98)	44 **Ru** Ruthenium 101.1	45 **Rh** Rhodium 102.9	46 **Pd** Palladium 106.4	47 **Ag** Silver 107.9	48 **Cd** Cadmium 112.4	49 **In** Indium 114.8	50 **Sn** Tin 118.7	51 **Sb** Antimony 121.8	52 **Te** Tellurium 127.6	53 **I** Iodine 126.9	54 **Xe** Xenon 131.3
55 **Cs** Cesium 132.9	56 **Ba** Barium 137.3	57 **La** Lanthanum 138.9	72 **Hf** Hafnium 178.5	73 **Ta** Tantalum 180.9	74 **W** Tungsten 183.9	75 **Re** Rhenium 186.2	76 **Os** Osmium 190.2	77 **Ir** Iridium 192.2	78 **Pt** Platinum 195.1	79 **Au** Gold 197.0	80 **Hg** Mercury 200.6	81 **Tl** Thallium 204.4	82 **Pb** Lead 207.2	83 **Bi** Bismuth 209.0	84 **Po** Polonium (210)	85 **At** Astatine (210)	86 **Rn** Radon (222)
87 **Fr** Francium (223)	88 **Ra** Radium (226)	89 **Ac** Actinium (227)	104 **Rf** Rutherfordium (257)	105 **Db** Dubnium (260)	106 **Sg** Seaborgium (263)	107 **Bh** Bohrium (262)	108 **Hs** Hassium (265)	109 **Mt** Meitnerium (266)	110 **Ds** Darmstadtium (269)	111 **Rg** Roentgenium (272)	112	(113)	114	(115)	116	(117)	(118)

58 **Ce** Cerium 140.1	59 **Pr** Praseodymium 140.9	60 **Nd** Neodymium 144.2	61 **Pm** Promethium (147)	62 **Sm** Samarium 150.4	63 **Eu** Europium 152.0	64 **Gd** Gadolinium 157.3	65 **Tb** Terbium 158.9	66 **Dy** Dysprosium 162.5	67 **Ho** Holmium 164.9	68 **Er** Erbium 167.3	69 **Tm** Thulium 168.9	70 **Yb** Ytterbium 173.0	71 **Lu** Lutetium 175.0
90 **Th** Thorium 232.0	91 **Pa** Protactinium (231)	92 **U** Uranium 238.0	93 **Np** Neptunium (237)	94 **Pu** Plutonium (242)	95 **Am** Americium (243)	96 **Cm** Curium (247)	97 **Bk** Berkelium (247)	98 **Cf** Californium (249)	99 **Es** Einsteinium (254)	100 **Fm** Fermium (253)	101 **Md** Mendelevium (256)	102 **No** Nobelium (254)	103 **Lr** Lawrencium (257)

☐	Metals
▨	Metalloids
▨	Nonmetals

The 1–18 group designation has been recommended by the International Union of Pure and Applied Chemistry (IUPAC) but is not yet in wide use. In this text we use the standard U.S. notation for group numbers (1A–8A and 1B–8B). No names have been assigned for elements 112, 114, and 116. Elements 113, 115, 117, and 118 have not yet been synthesized.

To our students who make it worthwhile.

Preface

Following the format of previous editions, the third edition of *Principles of Environmental Engineering and Science* is designed for use in an introductory sophomore-level engineering course. Basic, traditional subject matter is covered. Fundamental science and engineering principles that instructors in more advanced courses may depend upon are included. Mature undergraduate students in allied fields—such as biology, chemistry, resource development, fisheries and wildlife, microbiology, and soils science—have little difficulty with the material.

We have assumed that the students using this text have had courses in chemistry, physics, and biology, as well as sufficient mathematics to understand the concepts of differentiation and integration. Basic environmental chemistry and biology concepts are introduced at the beginning of the book.

Materials and energy balance is introduced early in the text. It is used throughout the text as a tool for understanding environmental processes and solving environmental problems. It is applied in hydrology, sustainability, water quality, water and wastewater treatment, air pollution control, as well as solid and hazardous waste management.

Each chapter concludes with a list of review items, the traditional end-of-chapter problems and discussion questions. The review items have been written in the "objective" format of the Accreditation Board for Engineering and Technology (ABET). Instructors will find this particularly helpful for directing student review for exams, for assessing continuous quality improvement for ABET and for preparing documentation for ABET curriculum review.

The third edition has been thoroughly revised and updated. The following paragraphs summarize the major changes in this edition.

- Introduction
  Data on per capita water consumption has been updated
- Biology
  Addition of sections on enzyme kinetics and rates of cellular respiration
  Expanded section on microbial transformations
  Problems related to enzyme kinetics, rates of cellular respiration, and thermodynamics of biologically mediated reactions
- Chemistry
  New section on equilibrium among gases and liquids
- Ecosystems
  Updated figures and charts
- Risk
  Updated tables
- Hydrology
  New section on water rights
  New section on storm water management
- Sustainability
  Major revision with a detailed discussion of water resources focusing on floods and droughts with examples in the United States and in other countries
  Updated tables and figures on energy and mineral resources

- Water Quality Management
  Updated figures and charts
  New section on water source protection
- Water Treatment
  Expanded overview of treatment systems
  New section on coagulation theory
  New section on membranes
  Expansion of section on disinfection to include breakpoint chlorination and UV disinfection
- Wastewater Treatment
  Material dealing with on-site disposal has been moved to a student website
  Addition of a discussion of biological treatment of nitrogen and phosphorus
  Addition of a discussion of Integrated Fixed Film Activated Sludge (IFAS)
  Addition of a discussion of Moving Bed Biofilm Reactor (MBBR)
  Revised and updated discussion of anaerobic digestion
- Air Pollution
  Updated ambient air pollution standards
  Addition of EPA methods for estimating emissions from power plants
  Addition of Federal Motor Vehicle Standards
  Discussion of CAFE standards
  Update of global warming discussion
  Addition of global warming potential data for selected compounds
  Addition of air-to-fuel ratio calculations
- Solid Waste
  Updated figures and charts

Cover Photographs

The photographs were chosen to represent the diverse aspects of environmental science and engineering covered in this text. The upper photograph of Mont Blanc and the French and Italian Alps was taken from Aiguille du Midi, overlooking Chamonix, France. As discussed in Chapters 5 and 12, global climate change has had very significant effects on glaciers and alpine ecosystems.

From left to right, the figures on the bottom represent various aspects of environmental engineering. The photo on the left is taken of the Tollgate Stormwater Management System, a constructed wetland project built to handle storm water from a subdivision in Lansing, Michigan. The water is naturally filtered and cleansed, solving complex environmental and water management problems and ensuring that pollutants are not discharged to Red Cedar or Grand Rivers, which flow through Lansing. The entire project cost less than one-third of that required for traditional solutions.

The next photo is of Singapore's Ulu Pandan Water Reclamation Plant. The plant treats 361,000 m^3 of wastewater per day using membrane bioreactors. Off-gas treatment is used for odor control. The effluent from the wastewater plant is further purified using advanced membrane technologies and ultraviolet disinfection and is marketed as NEWater, primarily for nonpotable industrial uses, although a small portion is blended with reservoir water for human consumption.

The third photo from the left is of the Garreg Ddu Reservoir, which is part of the Elan Valley Reservoir system in Wales, United Kingdom. The Elan Valley Reservoirs were constructed in the 19th century to serve the rapidly growing population of Birmingham, England. The city's expansion during the Industrial Revolution had resulted in regular outbreaks of such waterborne diseases as typhoid, cholera, and dysentery, resulting in the need for a source of clean, pure water. The reservoir system, although now privately owned by Glas Cymru, continues to serve Birmingham.

The photo on the far right is taken in the filtration room of the John Dye Water Conditioning Plant, which was built during the Great Depression and continues to serve the Lansing area. It opened in 1940, and with its art deco architecture and three sets of Depression-era murals, including one by Charles Pollock, brother to renowned artist Jackson Pollock, it is recognized as an architectural icon. It produces 87,000 m^3 of softened, clean drinking water to its customers every day.

Online Resources

An instructor's manual and set of PowerPoint slides are available online at www.mhhe.com/davis for qualified instructors. Please inquire with your McGraw-Hill representative for the necessary access password. The instructor's manual includes sample course outlines, solved example exams, and detailed solutions to the end-of-chapter problems. In addition, there are suggestions for using the pedagogic aids in the next.

As always, we appreciate any comments, suggestions, corrections, and contributions for future revisions.

Mackenzie L. Davis
Susan J. Masten

Acknowledgments

As with any other text, the number of individuals who have made it possible far exceeds those whose names grace the cover. At the hazard of leaving someone out, we would like to explicitly thank the following individuals for their contribution.

The following students helped to solve problems, proofread text, prepare illustrations, raise embarrassing questions, and generally make sure that other students could understand it: Shelley Agarwal, Stephanie Albert, Deb Allen, Mark Bishop, Aimee Bolen, Kristen Brandt, Jeff Brown, Amber Buhl, Nicole Chernoby, Rebecca Cline, Linda Clowater, Shauna Cohen, John Cooley, Ted Coyer, Marcia Curran, Talia Dodak, Kimberly Doherty, Bobbie Dougherty, Lisa Egleston, Karen Ellis, Elaheh Esfahanian, Craig Fricke, Elizabeth Fry, Beverly Hinds, Edith Hooten, Brad Hoos, Kathy Hulley, Geneva Hulslander, Lisa Huntington, Angela Ilieff, Melissa Knapp, Alison Leach, Gary Lefko, Lynelle Marolf, Lisa McClanahan, Tim McNamara, Becky Mursch, Cheryl Oliver, Kyle Paulson, Marisa Patterson, Lynnette Payne, Jim Peters, Kristie Piner, Christine Pomeroy, Susan Quiring, Erica Rayner, Bob Reynolds, Laurene Rhyne, Sandra Risley, Carlos Sanlley, Lee Sawatzki, Stephanie Smith, Mary Stewart, Rick Wirsing, Ya-yun Wu. To them a hearty thank you!

The authors would also like to thank Pamela Augustine, Brandon Curtas, David Desteiger, Cheryl Edson, John Engle, Timothy Greenleaf, Erin Henderson, Robert Little, Kate Logan, Jeremy Mansell, Lorna McTaggart, Kelly Mlynarek, Brad Osinski, Alicja Pawlowska, Shannon Simpson, Lindsay Smith, Bryan Stramecki, Brad Vernier, Marcie Wawzysko, and Adam Wosneski who also helped proofread the text, check problems and make the book more readable for students. In addition, we wish to thank Rebecca Masten-Davies for her assistance with providing a cultural experience for students by naming cities, rivers, lakes, etc. after mythological beings from the world over.

We would also like to thank the following reviewers for their many helpful comments and suggestions: Max Anderson, University of Wisconsin–Platteville; Gregory Boardman, Virginia Tech; Jonathan Brant, University of Wyoming; Leonard W. Casson, University of Pittsburgh–Swanson School of Engineering; Andres Clarens, University of Virginia; Lubo Liu, California State University–Fresno; George Murgel, Boise State University; John Novak, Virginia Tech; Jonathan Sharp, Colorado School of Mines.

We give special thanks to Simon Davies for his contributions. His efforts are sincerely appreciated. And last, but certainly not least, we wish to thank our families who have put up with us during the writing of this book, especially Rebecca and Jeffrey Masten-Davies, who gave up several Christmas vacations plus many other days during the year while their mom spent uncountable hours working on this book.

A special thanks to Mack's wife, Elaine, for putting up with the nonsense of book writing.

Mackenzie L. Davis Susan J. Masten

About the Authors

Mackenzie L. Davis, Ph.D., P.E., BCEE, is an Emeritus Professor of Environmental Engineering at Michigan State University. He received all his degrees from the University of Illinois. From 1968 to 1971 he served as a Captain in the U.S. Army Medical Service Corps. During his military service he conducted air pollution surveys at Army ammunition plants. From 1971 to 1973 he was Branch Chief of the Environmental Engineering Branch at the U.S. Army Construction Engineering Research Laboratory. His responsibilities included supervision of research on air, noise, and water pollution control and solid waste management for Army facilities. In 1973 he joined the faculty at Michigan State University. He has taught and conducted research in the areas of air pollution control and hazardous waste management.

In 1987 and 1989–1992, under an intergovernmental personnel assignment with the Office of Solid Waste of the U.S. Environmental Protection Agency, Dr. Davis performed technology assessments of treatment methods used to demonstrate the regulatory requirements for the land disposal restrictions ("land ban") promulgated under the Hazardous and Solid Waste Amendments.

Dr. Davis is a member of the following professional organizations: American Chemical Society, American Institute of Chemical Engineers, American Society for Engineering Education, American Meteorological Society, American Society of Civil Engineers, American Water Works Association, Air & Waste Management Association, Association of Environmental Engineering and Science Professors, and the Water Environment Federation.

His honors and awards include the State-of-the-Art Award from the ASCE, Chapter Honor Member of Chi Epsilon, Sigma Xi, election as a Fellow in the Air & Waste Management Association, and election as a Diplomate in the American Academy of Environmental Engineers with certification in hazardous waste management. He has received teaching awards from the American Society of Civil Engineers Student Chapter, Michigan State University College of Engineering, North Central Section of the American Society for Engineering Education, Great Lakes Region of Chi Epsilon, and the Amoco Corporation. In 1998, he received the Lyman A. Ripperton Award for distinguished achievement as an educator from the Air & Waste Management Association. In 2007, he was recognized as the Educational Professional of the Year by the Michigan Water Environment Association. He is a registered professional engineer in Michigan.

Dr. Davis is the author of a student and professional edition of *Water and Wastewater Engineering* and co-author of *Introduction to Environmental Engineering* with Dr. David Cornwell.

In 2003, Dr. Davis retired from Michigan State University.

Susan J. Masten is a Professor in the Department of Civil and Environmental Engineering at Michigan State University. She received her Ph.D. in environmental engineering from Harvard University in 1986. Before joining the faculty at Michigan State University in 1989, she worked for several years in environmental research at the University of Melbourne (Australia) and at the US Environmental Protection Agency's Kerr Laboratory, in Ada, Oklahoma. Professor Masten's research involves the use of chemical oxidants for the remediation of soils, water, and wastewater. Her research is presently focused on the use of ozone for reducing the concentration of disinfection by-products in drinking water, controlling fouling in membranes, and reducing the toxicity of ozonation by-products formed from the ozonation of polycyclic aromatic hydrocarbons and pesticides. She also had research projects involving the use of ozone for the reduction of odor in swine manure slurry and the elimination of chlorinated hydrocarbons and semivolatile organic chemicals from soils using in-situ ozone stripping and ozone sparging.

Dr. Masten is a member of the following professional organizations: Air and Waste Management Association, International Ozone Association, and the American Society for Engineering Education. She served on the Executive Committee of the MSU Chapter of the American Chemical Society from 1995–2005.

Professor Masten was a Lilly Teaching Fellow during the 1994–1995 academic year. She is also the recipient of the Withrow Distinguished Scholar Award, College of Engineering, MSU, March 1995, and the Teacher-Scholar Award, Michigan State University, February 1996, and the Withrow Teaching Award in 2012. Dr. Masten was also a member of the Faculty Writing Project, Michigan State University, May 1996. In 2001, she was awarded the Association of Environmental Engineering and Science Professors/Wiley Interscience Outstanding Educator Award.

Dr. Masten is a registered professional engineer in the state of Michigan.

Contents

4 Materials and Energy Balances 143

5 Ecosystems 189

6 Risk Perception, Assessment, and Management 233