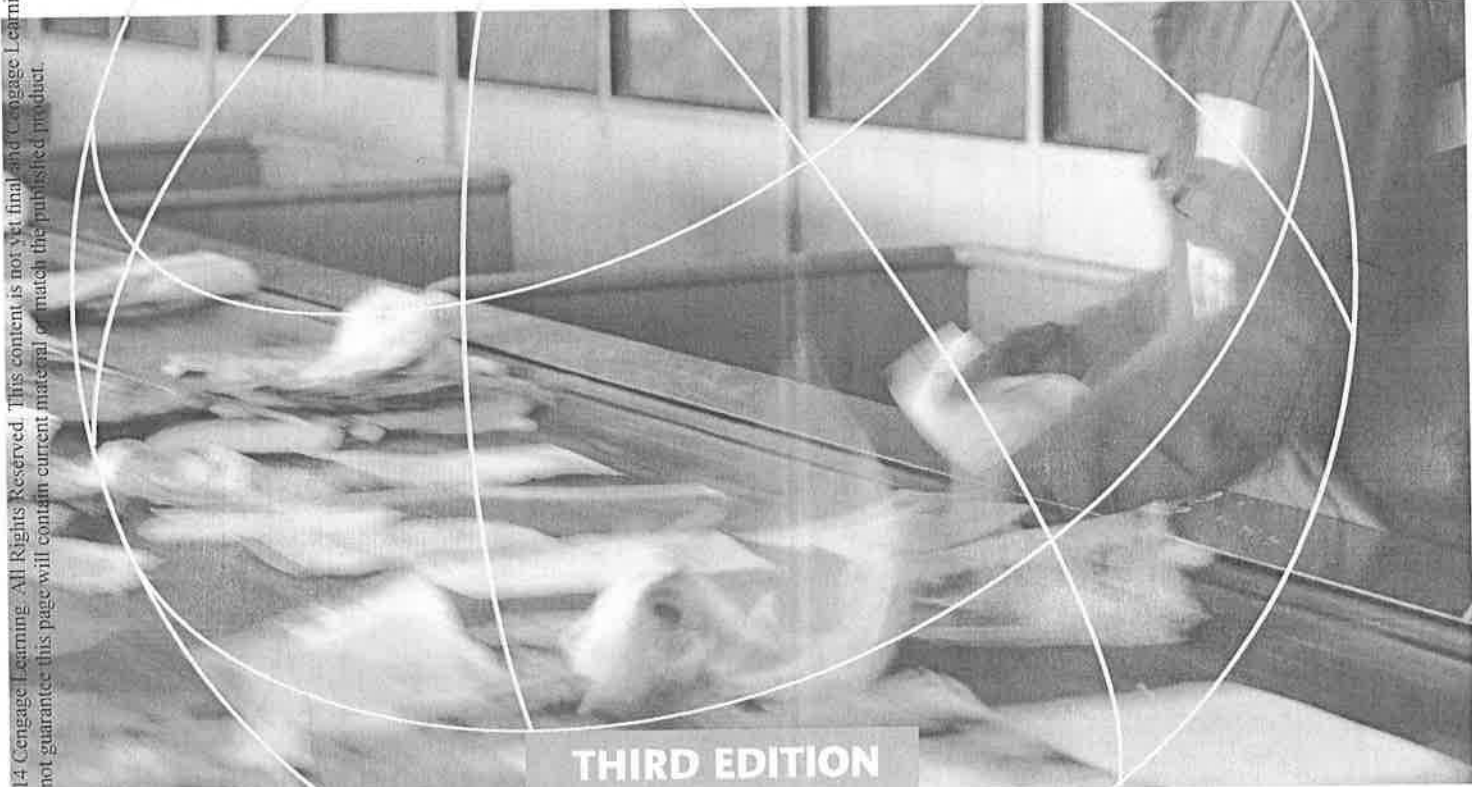


Solid Waste ENGINEERING

A Global Perspective

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THIRD EDITION

William A. Worrell • P. Aarne Vesilind • Christian Ludwig

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Integrated Waste Management
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Cover and Internal Designer: Imbue Design

Cover Image: James Hardy/ PhotoAlto
Agency RF Collections/Getty Images

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Library of Congress Control Number: 2015956726

ISBN: 978-1-305-63520-3

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Printed in the United States of America
Print Number: 01 Print Year: 2015

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DEDICATION

This book reflects a lifetime of work in the solid waste management field and would not have been possible without the influence of many people during my career. First and foremost would have to be Dr. Aarne Vesilind who provided guidance to a young engineering student at Duke University, hired him to perform a shredded acceptance test, and coauthored a paper that was published by the American Society of Mechanical Engineers. In addition, Frank McAlister inspired me at Duke to finish graduate school. At Brown and Caldwell, Jim Smith and Larry Theisen served as mentors. Joe Ruiz and Tony Sobrino smoothed the transition from the private sector to the public sector at Miami-Dade County. In San Diego County, Rick Anthony and Bow Bowman provided valuable insight. In San Luis Obispo, my staff: Carolyn Goodrich, and Patti Toews, along with Charles Tenborg, Ray Biering, Mike di Milo, Mary Whittlesey, and Ron Munds make my job easy. Finally the San Luis Obispo County Integrated Waste Management Authority Board of Directors, consisting of 13 elected officials, has shown me how elected officials can be dedicated, hard working, and a force for positive change and a real pleasure to work for.

No dedication would be complete without mentioning my family. My children, Hilary, Emily, Michael, and Sarah, who I have driven for two hours around Maui to Hana—not to see waterfalls, but to see the Hana Landfill along with many other landfills, recycling centers, and transfer stations over the years. To my daughter-in-law Lauren, son-in-laws Greg and Ryan, granddaughter Bridget, and grandsons Oliver and Ben, thanks for keeping me young. Finally, to the love of my life, my wife Kathy, who typed my thesis 37 years ago and helped me with this book. When we were just married and I was in graduate school, we went on a field trip to a large wastewater treatment plant. I asked her, wasn't it fascinating to learn what happens when you flush your toilet, and she said there were some things she just didn't care about. Thank goodness she never felt that way about garbage or me.

William A. Worrell

Sometime in the mid-1970s, the threat of nationwide bottle legislation (placing a mandatory deposit on beverage containers to encourage their recycling) prompted some of the large beverage manufacturers like Anheuser-Busch and Pepsi Cola to fund the National Center for Resource Recovery. This organization had a clear agenda—to promote the recovery of waste materials as an alternative to the much-dreaded bottle law. After some years, when the threat of such legislation had abated, the funding for NCRR dried up, and the organization disbanded. While it was operational, however, it produced many fine research publications and provided the funds and ideas for a number of university research programs, including the one at Duke University. Much of the research into the mechanics and policy aspects of materials recovery reported in this book came as a direct result of this support from the NCRR. The president of NCRR was James Abert, and its chief technical officer was Harvey Alter. Their friendship and encouragement was instrumental in my undertaking my own research in municipal solid waste processing, and thus, I would like to dedicate my part of this book to these two gentlemen.

P. Aarne Vesilind

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I dedicate my work to all persons who contributed to the success of my professional career. In the text below I summarize some key moments in my life and name persons who positively influenced and catalyzed my thinking.

Hans-Peter Seiler was my physics and chemistry teacher at the secondary school Seidenberg in Muri BE. His classes lightened a flame in me that is still burning today. First years at Freies Gymnasium Berne (FGB) followed but without chemistry classes. However, I continued to do chemistry experiments in the basement of the home of my parents, and later I expanded the laboratory at my grandmother's place. I thank my parents and my grandmother who gave me this unique opportunity.

For my home laboratory I urgently needed chemicals which were very difficult to obtain as they were harmful or toxic. *Ueli Roth*, the chemistry teacher at FGB, helped me out. His classes, which I joined later, further encouraged me to study chemistry at the university. Of course, I had to pay the chemicals from my pocket money. But, it turned out, the more toxic the chemicals, the cheaper they are. I shared my hobby with friends and colleagues. *Silvan Perego* joined me in my home laboratory, and we have spent many exciting laboratory experiences together. Thanks Silvan.

In 1989 I joined the research group of *Paul W. Schindler* at the University of Berne as a master student. I was fascinated by the chemical-physical behavior of solutions. Questions, such as "what are the forces which cause the formation of complexes in solutions?" or "why is it possible that something precipitates form a solution to become a solid?" triggered my motivation. Paul was among the first chemists who studied environmental systems. He was supported by *Geri Furrer*, today professor at ETH Zürich in Environmental Geochemistry, and *Laurent Charlet*, today professor of Water Geochemistry at University of Grenoble. Paul, Geri, and Laurent were very interesting discussion partners. With their support I have obtained my basic knowledge in geochemistry. I am very thankful for the time we worked together. As last PhD student of Paul, I obtained an essential gift—he shared his life time experience with me. Besides environmental chemistry we both enjoyed smoking the pipe, and we had many companionable discussions, often spiced with chemical content. Geri and Paul helped me to put "chemistry" into a larger environmental context.

In this life phase I met my future wife, Brigitte. She is not a scientist, but she may know better than anyone else what it means to work as a passionate scientist. I thank her for the patience she had with me over the many years. After my master and PhD studies we got married and moved to California for my postdoc. I obtained a position in the laboratory of *Bill Casey* at UC Davis to study dissolution processes of minerals. I am most grateful to Bill for his professional and personal support during our stay in Davis, his friendship, and the gorgeous time we have spent together. The most exciting ideas we developed during the sandwich lunches at the weekends and our walks from Hoagland Hall to Third Street. In a very short period we co-authored several papers and even two in the journal *Nature*.

Dissolution of minerals? You may wonder what this is good for. The person who knew it was *C. Annette Johnson*, a senior geochemist at Eawag, who worked on landfills containing waste incineration residues. She was worrying about toxic metals that may leach out. Annette offered me the opportunity to join her group which

was part of the laboratory of *Peter Baccini* at Eawag and gave me the possibility to perform my first field investigations. The decision to join the laboratory of Peter determined my later career to a great extent. His spirit and leadership concerning sustainable waste and resources management has not only impressed me but influenced the thinking of an entire generation of waste engineers and scientists, waste managers, recycling and waste treatment companies, as well as authorities. One could say the Swiss Law on Waste would not be the one it is today without Peter Baccini.

After the time at Eawag I joined a project at Paul Scherrer Institute. The goal of the project was to recover heavy metals from incineration residues. I was suddenly convinced that it makes no sense to study how we pollute the environment but that it was time to do something against it. *Samuel Stucki* was my superior, coach, and friend during all the years from 1997 to 2008 at the Energy and Materials Cycles laboratory of PSI. We shared all joy and worries. We understood each other so well that often we only had to look at each other in order to know what the other was thinking. With few exceptions, mostly we were of one mind. Supported by Samuel, I started one of my most exiting projects together with *Stefanie Hellweg*, today professor and chair of Ecological Systems Design at ETH Zürich. The result of this project was the book *Municipal Solid Waste Management*, which we published in 2003. It was a book for professionals but was the basis for my course Advanced Solid Waste Treatment that I taught at EPFL during the last decade. My arrival at EPFL in 2005 was not an easy one also because of the large distance between Paul Scherrer Institute and EPFL. In this context I would like to thank *Alexander Wokaun*, head of the General Energy Research Department at PSI, who supported me to successfully pass the challenges that came along with this complex arrangement.

Today's challenges in waste and resources management can only be tackled by inter- and transdisciplinary exchange. *Xaver Edelmann* was the father of different such exchange platforms such as the R'World Congress, where I have also met the first time with William A. Worrell back in 1999. With Xaver's support I later obtained the opportunity to contribute to the development of World Resources Forum.

After 10 years of teaching the course Advanced Solid Waste Treatment at EPFL and 12 years after publishing *Municipal Solid Waste Management*, it was time to think about a textbook for my students that corresponds with their needs. I thank *François Golay*, director of the Section of Environmental Engineering and Marilyne Andersen, the dean of our school, who both agreed that I take a partial sabbatical to make a contribution to *Solid Waste Engineering*. I thank Bill Worrell and his wife Kathy for the hospitality during my short stay at San Luis Obispo. The authors enjoyed the writing and I hope that you will enjoy the learning.

Christian Ludwig

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PREFACE

A Tale of Two Barges and Birds Dying from Plastics

Not so very long ago, as the coastal cities of the young United States grew to metropolitan regions, the disposal of municipal refuse was expediently achieved by simply loading up large barges, transporting them some distance from shore, and shoveling the garbage into the water. One such scow operated out of New York City during the turn of the 20th century; it is pictured below. Few complained when some of the refuse floated back to the shore. It was simply the way things were done.



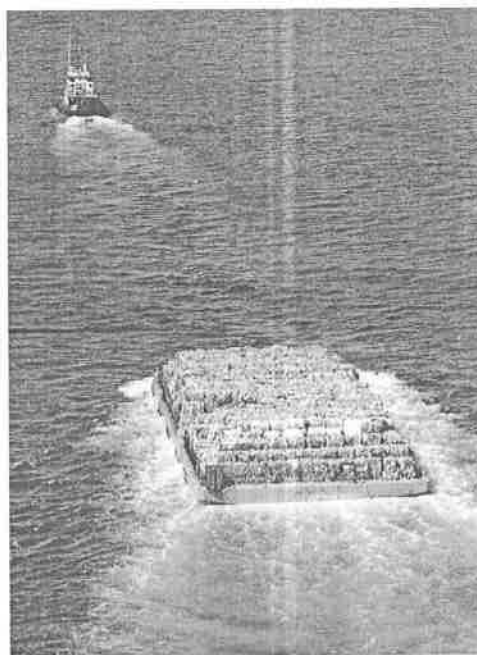
(Public Domain)

A different story can be told about another barge, named the *Mobro*, pictured on the next page. The year was 1987. The *Mobro* had been loaded in New York with municipal solid waste and found itself with nowhere to discharge the load, and ocean disposal was now illegal. The barge was towed from port to port, with six states and three countries rejecting the captain's pleas to offload its unwanted cargo.

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Mobro garbage barge (AP/World Wide Photos)

The media picked up on this unfortunate incident and trumpeted the “garbage crisis” to anyone who would listen. Reporters honed their finest hyperbole, claiming that the barge could not unload because all of our landfills were full and that the United States would soon be covered by solid waste from coast to coast. Unless we did something soon, they claimed, we could all be buried in garbage.

The difference between the two barges, almost 100 years apart in time, is striking. In 1900, there were few laws restricting refuse disposal, and thus, solid waste disposal practices resulted in severe and permanent detrimental effects to the environment. There is no doubt that much of the refuse being shoveled off the barge 100 years ago is still on the bottom of the New York Bight and will remain there indefinitely as an embarrassment to future generations.

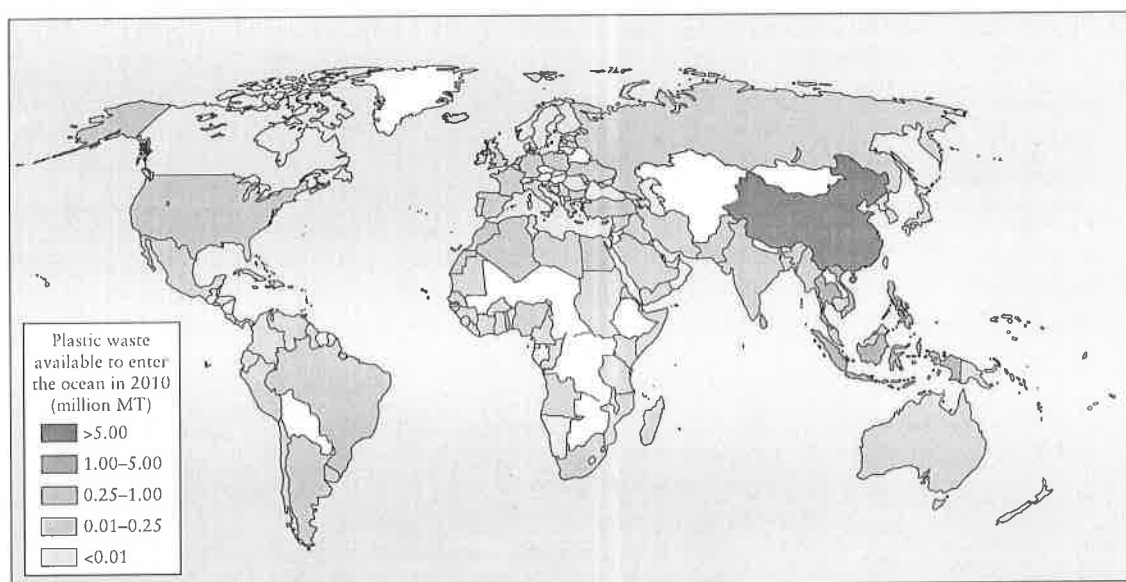
A hundred years later, the public is acutely aware of the problem of solid waste disposal, and today we have achieved a degree of technological sophistication in our management of solid waste. Our landfills are constructed with almost no detrimental environmental effect, our solid waste combustors emit essentially no pollutants, and the public is increasingly participating in recycling programs. We have the problem under control, and yet the public perception is exactly opposite of the reality, as exemplified by the *Mobro* incident.

The story of the hapless *Mobro* is actually a story of an entrepreneurial enterprise gone sour. An Alabama businessman, Lowell Harrelson, wanted to construct a facility for converting municipal refuse to methane gas. He recognized that baled refuse would be the best form of refuse for that purpose. He purchased the bales of municipal solid waste from New York City and was going to find a landfill somewhere on the East Coast or in the Caribbean where he could deposit the bales and start making methane. Unfortunately, he did not get the proper permits for bringing refuse into various municipalities, and the barge was refused permission to offload

its cargo. As the journey continued, the press coverage grew, and no local politicians would agree to allow the garbage to enter their ports. Harrelson finally had to burn his investment in a Brooklyn incinerator.

The barge *Mobro* is a poor metaphor for the state of municipal solid waste management, because today we manage the discards of society with engineering skill at reasonable cost and at minimal risk to the public. This is not to say that we cannot do things better. Yes, we have to be concerned about nonreplenishable resources. Yes, we care about the use of land for refuse storage—land that could be used for other purposes. Yes, we can design better packaging for our consumer goods. Yes, we can initiate programs that promote litter-free roads and keep litter out of our oceans. Yes, we can design better devices that more effectively separate the various constituents of refuse. Yes, we can develop solid waste management strategies that promote zero waste. And yes, we can do many good things to improve the solid waste collection, treatment, and disposal process. But we also should be proud of the accomplishments of solid waste engineers in managing the collection, recovery, and disposal of municipal refuse. It is this positive theme that we wish to impress on the readers of this book.

In the first and second editions, most of the focus was on the United States. However solid waste is a global issue as we start to consider our limited resources, impact of pollution on our oceans and global warming. Solid waste from Fukushima, Japan has been found on the west coast of the United States. E-waste has become a problem of global dimension as toxic wastes are transported between different continents, and an ecological treatment is not always guaranteed. Waste gyros exist in the oceans. In 2010 275 million metric tons of plastic waste were generated in 192 coastal countries, with 4.8 to 12.7 million metric tons entering the ocean.^{X1} Worldwide, many countries, such as Italy, have recurring



^{X1} Jenna R. Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Lavender Law, K., 2015. Plastic waste inputs from land into the ocean. 347(6223):768–771

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Wastes in the streets of Napoli

waste management problems. In Napoli the army's help was needed in the past to remove the garbage from the streets. At the same time, other countries are also developing advanced new practices for integrated waste management. Because of the significance of this global approach, Dr. Christian Ludwig from Switzerland has been added as a co-author. In addition the third edition has been reorganized to reflect the hierarchy of waste management. For example, landfilling, the last option for waste management, has been moved to the end of the book.

This book is written for the student who wants to learn about solid waste engineering, a subset of environmental engineering. Environmental engineering developed during the last 60 years as a major engineering discipline and is now established as an equal alongside such major engineering fields as civil, chemical, biological, mechanical, and electrical engineering. The emergence of environmental engineering is driven in great part by societal need to control the pollution of our environment. Jobs for environmental engineers continue to increase, and there is no sign that this will slow down.

Using this book as part of a graduate or advanced undergraduate course will help to prepare the student to enter the field. Much of the knowledge in solid waste engineering is gained by actual experience while working with experienced engineers in the field, and it is impossible to include all of this experience in this book. What we hope is that the student, at the conclusion of this course, will be able to enter into meaningful conversations with experienced engineers and eventually put the basic principles learned in this course to beneficial use.

The course, as taught at different universities, usually takes one semester. Some have taught this course by going through the book in sequence, assigning homework problems as appropriate. Others have eschewed homework problems completely and used only a design problem, such as the one found in Appendix A, requiring

students to work in groups and individually write weekly chapters. The structure of the course is probably not as important as the education of the students in the fundamentals of solid waste management. It is not enough to train students to solve certain types of problems. It is important for them to emerge from this course being able to think reflectively and logically about the problems in and solutions to solid waste engineering.

We believe that the material in this book represents a valuable first course in solid waste engineering. With this revision, we have updated information to reflect current conditions and changes that have occurred in solid waste technology—regulations and practices that have occurred over the past several years. For us, the “proof of the pudding” has been the wide acceptance of our students by the practicing engineering community. We hope that others will be able to use this book to launch exciting and productive careers in solid waste engineering.

We would like to thank Debra Reinhart, our co-author from the first edition, for her valuable contribution. In addition, thanks to Barry Shanoff, for his help on the legal issue of flow control, Peter Chromec for assistance with thermal processes and Richard Anthony for this help on zero waste. We would also like to thank the many reviewers of all three editions. Special thanks to the helpful people at Cengage Learning who were very patient with us. Finally to all our colleagues around the world whose knowledge and dedication inspire us every day, thank you.

William A. Worrell
P. Aarne Vesilind
Christian Ludwig

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ABOUT THE AUTHORS

WILLIAM A. WORRELL

William A. Worrell received a B.S. and M.S. in Civil Engineering from Duke University in 1976 and 1978, respectively. His Master's Thesis involved evaluating the separation efficiencies of various air classifiers. In 1989, he attended Harvard University's John F. Kennedy School of Government Summer Program for Senior Executives in State and Local Government. Mr. Worrell has published and/or presented 56 professional papers in the United States, England, Switzerland, Japan, Peru, Hong Kong, and China. He is a registered professional engineer in California, Georgia, and Florida.

In 1978, Mr. Worrell joined Brown and Caldwell Consulting Engineers in Atlanta and managed solid and hazardous waste projects throughout the south. Seven years later, he opened Brown and Caldwell's first Florida office. In 1987, he was hired by Miami-Dade County as their chief solid waste engineer. In 1990, he was hired to manage San Diego County's solid waste program, and five years later, he became the first manager of the San Luis Obispo County Integrated Waste Management Authority where he is currently employed. He has also taught the Solid Waste Engineering course at California Polytechnic State University in San Luis Obispo.

During his more than 37 year career, he has had numerous achievements and recognitions. In 1984, he wrote the feasibility study for the Marion County Oregon Waste to Energy Project Bonds—the first American plant to use a dry scrubber and baghouse. In Miami, he was responsible for closing a 640 acre superfund site, retrofitting the largest waste-to-energy plant, and selecting a curbside recycling program for over 200,000 homes. In San Diego, his recycling program was recognized by the National Recycling Coalition as a leading program in the United States. In San Luis Obispo, he implemented the first mandatory retail take-back programs for household batteries, sharps, and latex paint. This household hazardous waste program received the program excellence award from the North American Hazardous Materials Management Association in 2000, 2007, and 2011. In 1998, San Luis Obispo was one of first programs to meet California's 50% waste diversion goal, and by 2014, 67% of the waste was being diverted from landfills. In recognition of his leadership, the California Resource Recovery Association selected Mr. Worrell as the Recycler of the Year.

P. AARNE VESILIND

Following his undergraduate degree in civil engineering from Lehigh University, Vesilind received his PhD in environmental engineering from the University of North Carolina in 1968. He spent a post-doctoral year with the Norwegian Institute for Water Research in Oslo and a year as a research engineer with the Bird Machine Company. He joined the faculty at Duke University in 1970, where he served as chair of the Department of Civil and Environmental Engineering. In 1999, he

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was appointed to the R. L. Rooke Chair of the Historical and Societal Context of Engineering at Bucknell University. He served in this capacity until his retirement in 2006.

In 1976–1977, he was a Fulbright Fellow at the University of Waikato in Hamilton, New Zealand. He is a former trustee of the American Academy of Environmental Engineers, a past president of the Association of Environmental Engineering Professors, a Fellow of the American Society of Civil Engineers, and a registered Professional Engineer in North Carolina. He is the recipient of the Collingwood Prize awarded by the American Society of Civil Engineers. Other awards include the E. I. Brown Award from the students of the Department of Civil Engineering at Duke University for teaching excellence (four times), and the Tau Beta Pi Teaching Award from the students of the School of Engineering at Duke University.

While at Duke, he headed the Science, Technology, and Human Values program for many years, which was an undergraduate enrichment program that sought to build bridges between the humanities and engineering.

His research into the recovery of materials and energy from municipal solid waste led to many funded projects and numerous articles in professional journals. He has been the primary adviser for 12 PhD students and 46 master's students and has authored over 20 textbooks and other technical and professional books.

CHRISTIAN LUDWIG

Christian Ludwig received his master's degree (1990) and PhD (1993) from the Chemistry Department at the University of Berne, Switzerland. Post-doctoral years were spent at the Department of Land, Air, and Water Resources (LAWR), UC Davis, CA (1994–1995) and at the Swiss Federal Institute for Environmental Science and Technology EAWAG (1995–1997). Since 1997 he has worked at the General Energy Research Department of Paul Scherrer Institute (PSI).

In 2005 he was appointed adjunct professor at the École Polytechnique Fédérale de Lausanne (EPFL) in the field of Solid Waste Treatment. At EPFL he is mainly advising students of the Environmental Engineering Section (SIE). He is teaching the course Advanced Solid Waste Treatment, makes contributions to the laboratory class Pollutants Analysis in the Environment, and the interdisciplinary teaching course Urban Neighborhoods, Infrastructures, and Sustainable Development dedicated to students of architecture, civil and environmental engineering.

Christian Ludwig has chaired or co-chaired several large international conferences focusing on resources and waste management, such as REWAS and World Resources Forum. He had different consulting mandates for industry and governments. Additional landmarks of his occupational career are reflected in his dedication section.

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FOREWORD

With the third edition of *Solid Waste Engineering*, the authors have decided to expand this university textbook to focus on the worldwide problem of solid waste management. This change is illustrated by the addition of “A Global Perspective” to the title. Given that we are currently using our natural resources at an unsustainable rate, polluting our oceans and land with a variety of waste products, and altering our atmosphere with gases that are causing further global warming, now is the time to educate future engineers with knowledge and tools to address these worldwide problems.

The three co-authors all have significant international experience. For example, Dr. Ludwig is the chair of the World Resources Forum Scientific Committee, and Mr. Worrell is a member. In their official capacity they have interacted with experts from over 80 countries at conferences in Switzerland, China, and Peru. This international knowledge is reflected in the revisions to *Solid Waste Engineering*.

The third edition has been rearranged to follow the hierarchy of solid waste management, reduction, reuse, recycling, and recovery. Thus students will first learn about integrated waste management strategies, an expertise that will support the future engineer to take measures for pollution prevention as well as for resources conservation. In chapter 2 the students are introduced to municipal solid waste characteristics, including the identification of different waste components and materials. Component-specific information is needed for recovery, separation, and recycling of waste materials. The relevance of chemical, physical, and mechanical properties are discussed in more detail as a basis for the chapters that follow. These properties are most helpful in order to identify potentially meaningful recycling pathways as well as to decide about possible technological separation and purification options. The next chapter is dedicated to the collection of municipal solid waste, a key—but many times overlooked—component of integrated waste management. Following collection is mechanical processing, in most cases the necessary first step to the recycling and recovery of municipal solid waste. The students will then study mechanical, biological, and thermal processes. For each of these topics the authors have dedicated a separate chapter that will introduce the students to the basic principles of these separate disciplines in the context of waste management. Since not all waste streams can be recovered, students move on to residue management by combustion and landfilling. Finally, students are exposed to the current issues in solid waste management and the principles of integrated and sustainable solid waste management. This textbook is an excellent introduction into the field of solid waste engineering and covers most of the relevant topics.

The World Resources Forum envisions the world where influential decision makers, established civil societies, key industrial players, leading scientists and engineers, and the empowered public interact and communicate on setting the agenda and developing solutions on sustainable use of natural resources worldwide, paying close attention to the delicate interplay between the economic, social, and environmental implications of resource use as well as acknowledging the challenges of

increasing pressure on the availability of natural resources. Through this interaction of multiple stakeholders, innovative and effective solutions emerge, addressing the issue of efficiency and sufficiency of resource utilization among consumers, producers, and waste management, establishing sustainable practices of resources use worldwide.

Solid waste engineers are needed at the table when setting the agenda and developing solutions on sustainable use of natural resources. *Solid Waste Engineering* is an important tool that reflects the proper approach to solid waste management that students can use in their future endeavors, whether they are working as solid waste engineers for a local municipality or setting worldwide resources policy at the United Nations.

**Dr. Xaver Edelmann, President
World Resources Forum (www.wrforum.org)**

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